The impact of longline fishing on the seabirds breeding on Marion Island

by

Deon Charl Nel

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Frontispiece: Wandering albatross courtship display at Macaroni Bay, Marion Island

DECLARATION

This thesis reports the results of original research I conducted under the auspices of the Percy FitzPatrick Institute of African Ornithology, University of Cape Town, between 1998 and 2002. All assistance that I received has been fully acknowledged. This work has not been submitted for a degree at any other University

Deon C. Nel

To Jeanne, my family,

and the sight of an albatross on the open ocean

L'Albatros

Souvent, pour s'amuser, les homes d'équipage
Prennent des albatross, vastes oiseux des mers,
Qui suivent, indolents compagnons de voyage,
Le navire glissant sur les gouffres amers.

A peine les ont-ils deposes sur les planches,
Que ces rois de l'azur, maladoits et honteux,
Laissent piteusement leurs grandes ailes blanches
Comme les avirons trainer à côté d'eux.

Ce voyageur ailé, comme il est gauche et veule!
Lui, naguère si beau, qu'il est comique et laid!
L'un agrace son bec avec un brûle-gueule,
L'autre mime, et boitant, l'infirme qui volait!

Le poëte est semblable au prince des nuées
Qui hante la tempête et rit de l'archer;
Exilé sur le sol au mileu des huées.
Ses ailes de géant l'empêchent de marcher

Charles Baudelaire 1846

Freely translated[1]

Sometimes for fun, the seamen
catch albatrosses, great birds of the ocean.
Languid companions of the voyage, who follow
the ship, gliding over the cruel waves

When hauled on deck,
these kings of the sky become ungainly and absurd.
Sadly drooping their great white wings
like oars trailing in the water

How awkward and feeble is this winged traveller;
Once so beautiful, now comic and grotesque.
A sailor teases its beak with his pipe,
Another, limping, mimics the pathetic walk.

The poet is like a prince of the clouds,
Riding the storm and scorning danger.
Stranded on land, among jeering crowds,
His gigantic wings are a hindrance.

[1] Translation taken from Tickell W.L.N. 2000. *Albatrosses*. Pica Press, Sussex

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Abstract: This study describes the impact of longline fishing on the seabirds breeding on the sub-Antarctic Prince Edward Islands. The development of a demersal longline fishery for Patagonian toothfish *Dissostichus eleginoides* close to the islands with almost complete observer coverage during the study allowed a detailed examination of the impacts of this fishery. The vast majority of seabird mortalities were adult males that were breeding at the time they were killed. White-chinned petrels *Procellaria aequinoctialis* were killed most frequently, but albatrosses and giant petrels were also killed when lines were set in the daytime. Birds were killed almost exclusively during their breeding season, and albatrosses were caught closer to the islands than white-chinned petrels. It is estimated that between 8 500 and 18 500 birds could have been killed between 1996-2000, mostly due to high levels of Illegal Unregulated and Unreported (IUU) fishing. This is likely to have a significant impact on the breeding populations of several species of seabirds breeding on the Prince Edward Islands. A large increase in the amount of fishing gear found next to seabird nests as well as fishery-derived items in the diets of wandering albatrosses was recorded concurrent to the development of the toothfish fishery around the Prince Edward Islands. There was also an increase in the number of observed seabird entanglements in fishing gear and mortalities due to the ingestion of fishing gear.

The foraging ecology of wandering *Diomedea exulans* and grey-headed albatrosses *Thalassarche chrysostoma* is described in relation to known longline fishing areas. Both species varied their foraging distribution throughout the breeding season. During the early chick-rearing stage birds foraged closest to the island and showed the greatest overlap with the toothfish longline fishing areas, whereas during incubation and late chick-rearing birds moved further away from the island and overlapped more with tuna longline fisheries. Non-breeding wandering albatrosses moved farthest from the island and showed the greatest overlap with tuna fisheries. Males made more short foraging trips and spent more time in the toothfish longline fishing areas, whereas females foraged farther away from the island and spent more time in the warmer waters where pelagic tuna fishing is concentrated. Wandering albatross diet samples contained the most fishery-derived items during the early chick-rearing stage. The foraging distribution of wandering albatrosses on Marion Island and the neighbouring Crozet Islands overlapped partially during incubation and late-chick rearing, but were almost totally non-overlapping during the early chick-rearing stage. Tracking studies also showed how grey-headed albatrosses foraged at mesoscale oceanographic features of high productivity both at the Sub-tropical Front and the Antarctic Polar Front. As pelagic tuna fishing vessels also target such features at the Sub-tropical Front, this behaviour may mean that the overlap of albatross natural foraging areas and pelagic tuna longline fishing areas occurs at an even finer scale than previously thought.

Population trends of four large procellariforms (wandering albatross, grey-headed albatross, northern *Macronectes halli*, and southern giant petrels *M. giganteus*) breeding on Marion Island all showed similar broad scale trends. All were stable or decreasing slightly during the 1980s, increasing during the early 1990s, and stable or decreasing again during the late 1990s. Wandering albatross population counts on Marion were correlated with all other large Indian Ocean populations, but not with those from South Georgia, South Atlantic Ocean. Furthermore, annual adult survival rates of Marion Island wandering albatrosses were correlated with those measured on the Crozets Islands (Indian Ocean) but were different from those measured on South Georgia. This suggests that adults of Indian Ocean populations are affected by broad scale factors within the Indian Ocean. Changes in pelagic tuna longline fishing effort in the southern Indian Ocean can explain these trends. Adult and juvenile survival rates on Marion Island were most strongly correlated with Japanese pelagic longline fishing effort in the entire southern Ocean, as opposed to effort in the closer vicinity of Marion Island. This suggests that a significant portion of the mortality occurs when birds are foraging farther away from the islands, but still south of 40°S (the area mostly used by Japanese longline vessels). Female adult survival rate was significantly lower than males, confirming their higher vulnerability to the risk of mortality by pelagic tuna longlining due to their more northerly foraging distribution. High adult survival rates and consistently good breeding success was recorded since the start of the toothfish fishery around Marion Island, indicating that birds may derive some benefit from supplementary feeding on offal produced by these vessels.

Annual variability in population trends of wandering albatross and northern giant petrels as well as the proportion of first time breeders in wandering albatross study colonies were correlated with the annual maximum ENSO index. A simple, age-structured model revealed that the observed population increase in the early 1990s was the result of recovering adult and juvenile survival rates (presumably due to a decrease in pelagic longline fishing effort in the southern Indian Ocean). However, the observed increase in the number of breeding birds between 1994 and 1998 can only be explained by taking into account the observed changes in age of first time breeders and annual recruitment rates. The observed increase thus appears to be a result of an increase in the proportion of the population that breeds in a given year, rather than a real population increase. This serves as a warning that population decreases that may have occurred as a result of high levels of IUU fishing close to Marion Island, could be masked by changes in the proportions of the breeding population that is attempting to breed. This proportion can be affected by environmental (e.g. ENSO) as well as anthropogenic factors (e.g. level of supplementary feeding on offal).

General Introduction

GENERAL INTRODUCTION

The impact of longline fishing is regarded as the most critical conservation problem facing seabirds globally. Twenty two species of albatrosses and petrels currently listed as globally threatened, are killed in significant numbers when they attempt to snatch baited hooks being deployed from the stern of longline fishing vessels (BirdLife International 2000). Over 60 species of seabirds have been recorded killed in every major ocean sector by a growing number of longline fisheries (Brothers *et al.* 1999). These fisheries vary not only in their geographical distribution but also the technique used to set the lines, resulting in differing impacts on seabird populations. Although large scale extrapolations are very crude (for reasons described below) it is estimated that hundreds of thousands of seabirds are killed in this manner each year (e.g. Brothers 1991, CCAMLR 2000).

In an effort to simplify the many different longline fisheries and their effects, I will attempt to categorize them very broadly according to their potential to interact with seabirds. Firstly, longline fisheries can be separated spatially into two groups: those that occur in the near vicinity of the breeding islands of the affected seabirds and thus have the potential of interacting with adult birds during their breeding season, and those that occur at a distance from the breeding islands, outside the normal foraging range of breeding birds. Secondly, fishing technique can be divided into two broad groups: demersal and pelagic longlining. Demersal longlines have heavy weights attached at intervals causing the line to sink to the ocean floor, where the target fish species occur (Fig. 1). Demersal longlining takes place in the shallower waters of continental shelves and slopes, around some oceanic islands and seamounts. These fisheries are often located very close to the breeding colonies of threatened seabirds. Pelagic longlining, on the other hand, normally takes place in deeper water and is often concentrated at oceanographic fronts and other productive areas (Uozumi *et al.* 1997). Pelagic longlines have little weight attached and normally rely on the mainline sinking under its own weight (Fig. 1) (Brothers *et al.*1999). Thirdly, certain longline fisheries produce a large amount of offal in the form of bycatch species and processed discards of target species, whereas in other fisheries this is limited. Procellariiformes are known to derive substantial benefits from such supplementary sources of food

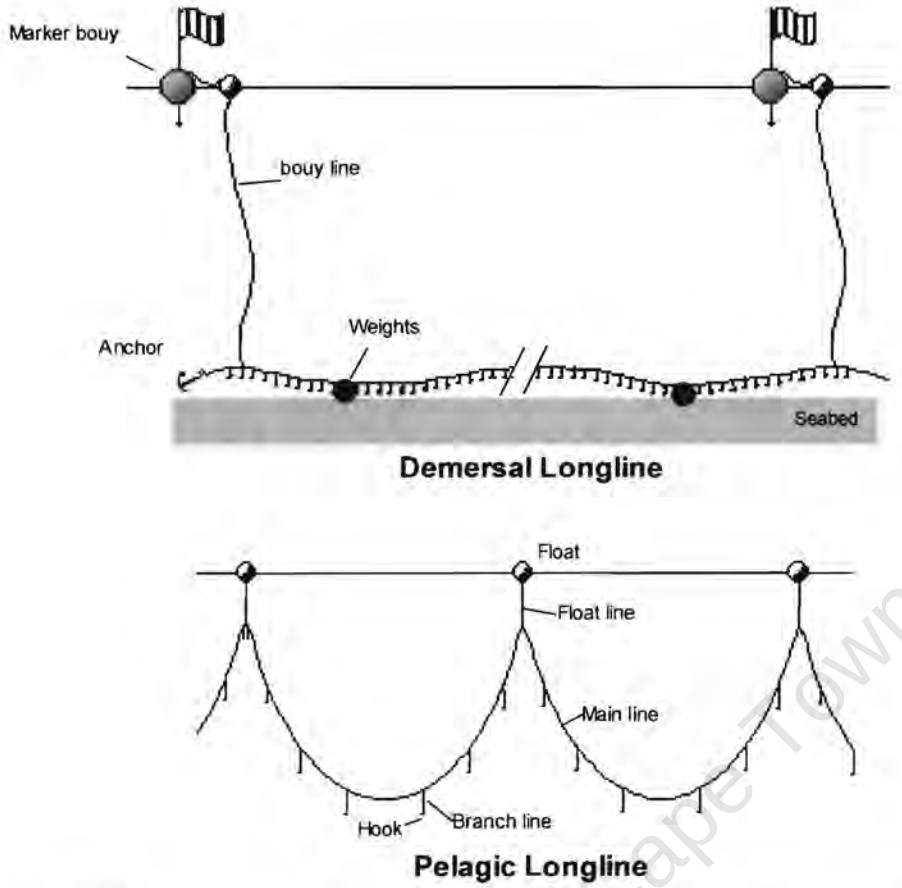

Figure 1. Schematic diagrams of the two major types of longlining. Redrawn fron Suzuki *et al.* (1977) and Bjordal & Lokkeborg (1996).

(e.g. Thompson 1992, Garthe *et al.* 1996), which can even influence their at-sea distribution (Ryan & Moloney 1988).

Species of the order Procellariiformes are the most severely threatened by longline fishing. Many procellariiforms have been renowned for following ships and scavenging of galley waste for centuries (e.g. Foster 1777). This behaviour may have developed from a natural behaviour of following cetaceans (e.g. Enticott 1986, Pitman & Balance 1992), scavenging either pieces of dismembered prey items (Ridoux 1987, Pitman & Balance 1992) or regurgitations from squid eating cetaceans (Clarke *et al.* 1981). It is this behaviour that now places several of these species under serious threat of extinction (BirdLife International 2000). However, within this group there are physical and behavioural differences between species that could affect their relative vulnerability to this threat, as well as possible benefits that they may derive from supplementary feeding. The most important physical variable is body size. Larger

albatrosses (e.g. the great albatrosses *Diomedea* spp.) and giant petrels *Macronectes* spp. may have an advantage when competing for offal scraps jettisoned from fishing vessels, whereas smaller albatrosses (e.g. the mollymawks *Thalassarche* spp.) and *Procellaria* petrels are more manoeuvrable and able to dive deeper (Prince *et al.* 1994, Huin 1995) and are thus able to get closer to the stern of the vessel and access faster sinking baits. One important behavioural variable is obviously foraging distribution, as this will affect the spatial overlap and potential interaction with longline fisheries. A second important behavioural variable is the time of day when the birds forage. Most albatrosses feed mainly by day, resting for most of the night on the surface (Croxall & Prince 1994), whereas the smaller *Procellaria* petrels are active by both day and night (Warham 1996).

It is thus clear that the impact of longline fishing on seabirds of a given locality is a product of complex set of interacting factors. Interpolating results from other localities could lead to a significant misunderstanding of the real impacts. It was with this in mind that this study was initiated at Marion Island. The aim of the study was to both assess the impacts and understand the interactions between longline fishing and the seabirds on Marion Island.

This study was conducted at sub-Antarctic Marion Island (46°54'S, 37°45'E). Marion Island and the smaller Prince Edward Island, located only 19 km to the north east, together make up the Prince Edward Islands group. These islands are a globally important breeding site for sub-Antarctic seabirds (Williams *et al.* 1979, Fishpool & Evans 2001), and the large number of procellariforms breeding on these islands is probably a result of their favourable geographic location (Fig. 2). The islands lie only 280 km north of the Antarctic Polar Front and 540 km south of the southern extent of the Sub-tropical Front (Belkin & Gordon 1996). Both these fronts display increased primary productivity that attracts large numbers of procellariforms (Pakhomov & McQuaid 1996). To the south, the Antarctic Polar Front is maintained in a more northerly position (and closer to the islands) by the South West Indian Ridge. The position where the Antarctic Polar Front crosses the South West Indian Ridge, has been identified as an area of enhanced variability and productivity (Pollard & Read 2001). To the north east of the islands, the Sub-tropical Front is deflected southwards (and closer to the islands) by the Agulhas Front (Belkin & Gordon 1996). The

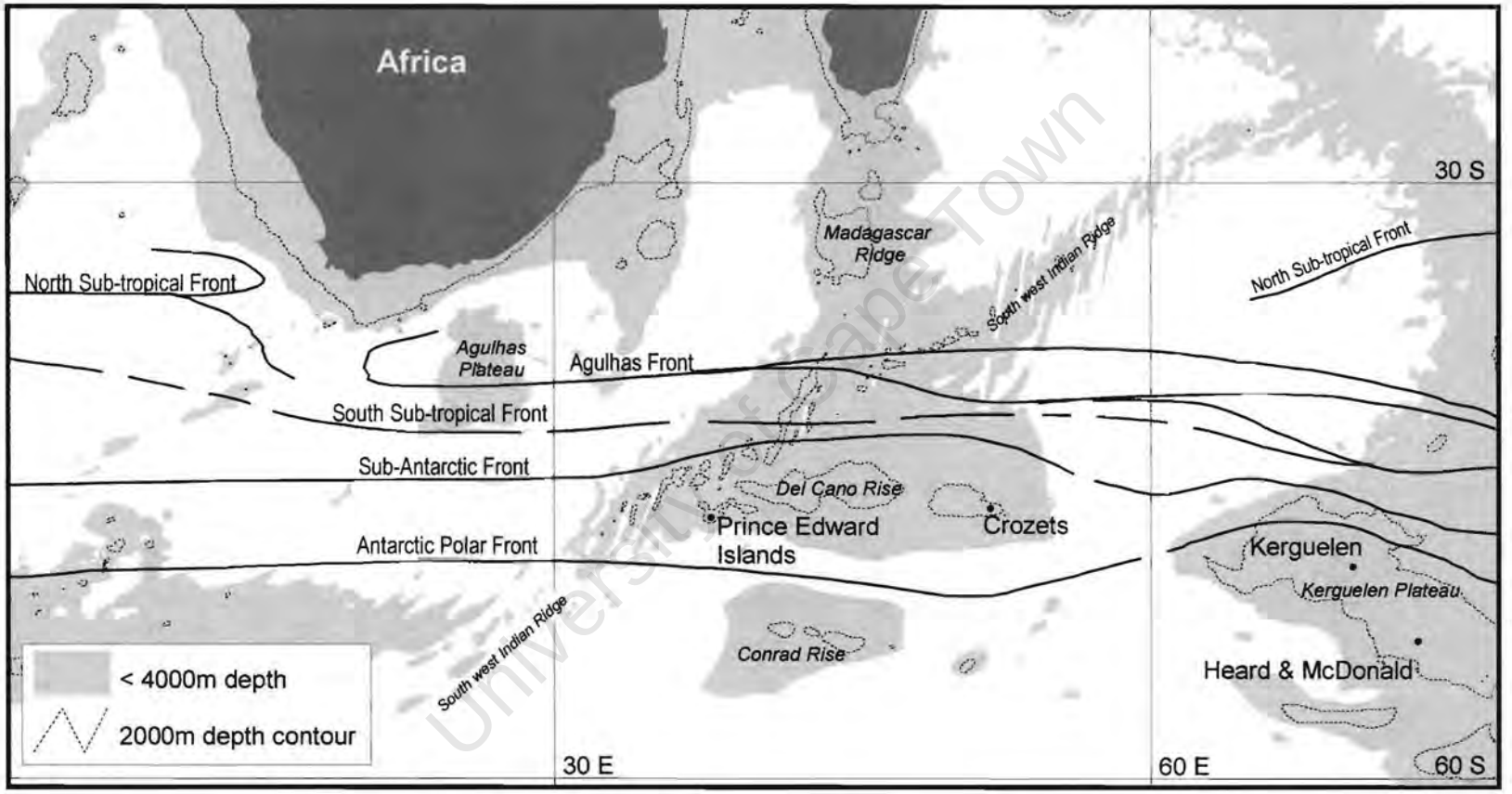

Figure 2. The location of the Prince Edward Islands (including Marion Island) in relation to the major oceanographic fronts (taken from Belkin & Gordon 1996) and bathymetric features.

Agulhas Front also increases the intensity (and thus productivity) of the Sub-tropical Front south of Africa, and this effect steadily decreases eastwards (Lutjeharms & Ansorge 2001).

However, this favourable location has its cost. Highly productive oceanographic fronts are also favoured foraging areas for tuna *Thunnus* spp. and consequently tuna longline fishing vessels (Uozumi *et al.* 1997). As a result the Prince Edward Islands lie close to an area of intense tuna longline fishing, south and south east of Africa (Tuck & Bulman 2001). Although tuna longline fishing effort in other parts of the Southern Indian Ocean has varied over time, the area south of Africa has remained one of the most intensely fished areas since the early 1970s (Tuck & Bulman 2001). In the Southern Hemisphere, pelagic longline fishing for tuna is regarded as the fishery with the greatest incidental take of albatrosses and other seabirds (Brothers 1991, Bergin 1997). This is due to the immense size of the fishery (*ca* 200 million hooks are set south of 30°S annually; Tuck & Bulman 2001) as well as the gear configuration (lines are not heavily weighted; Brothers *et al.* 1999).

During this study a new longline fishery developed close to the Prince Edward Islands. In the austral spring of 1996 sanctioned longlining for Patagonian toothfish *Dissostichus eleginoides* started within the South African Exclusive Economic Zone (EEZ), following large scale Illegal, Unregulated and Unreported (IUU) fishing in the months prior to this (Ryan *et al.* 1997). This is a demersal fishery and lines are typically set on shelf slopes in waters of *c.* 800-2500 m depth (Robertson 2000), although lines were almost exclusively set in waters of <2000 m depth in the Prince Edward Island fishery. The shelf area around the Prince Edward Islands is small compared to other sub-Antarctic Islands, resulting in lines either being set very close to the islands, or on Del Caño Rise (Fig. 2). However, the most important feature of the Patagonian toothfish fishery throughout the Southern Ocean has been large-scale IUU fishing, which could kill more than 100 000 seabirds in some years (CCAMLR 2000).

Thesis outline

Each chapter of this thesis has been written as an independent paper to facilitate publication of results. This has resulted in some overlap in the introductory sections of each chapter.

Chapter 1 analyses the impacts of the longline fishery for Patagonian toothfish around the Prince Edward Islands. This fishery was started during the first year of this study and all sanctioned vessels were required to carry an independent scientific observer. This gave an ideal opportunity to investigate the impacts of this fishery in detail over its first four years. Chapter 2 describes evidence of the impacts of this fishery on seabirds as observed from the island. Most importantly, this chapter describes the indirect impacts of adults feeding chicks pieces of fisheries gear or becoming entangled in such gear. These impacts are not measured by observers aboard fishing vessels and consequently are often overlooked when assessing the impacts of fisheries.

Chapters 3, 4 & 5 examine the foraging ecology of the two albatross species breeding on Marion Island that are most severely affected by the impacts of longline fishing: the wandering *Diomedea exulans* and grey-headed albatross *Thalassarche chrysostoma*. Chapters 3 and 4 study the spatial overlaps of the foraging distributions of these albatrosses with known longline fishing areas, and also look at their diets for direct evidence of interactions. Chapter 5 uses the same tracking and diet data presented in Chapter 4 to explore the ecological reasons why grey-headed albatrosses utilize the foraging areas that they do and how this might affect their exposure to the risk of incidental mortality in longline fisheries.

Chapters 6 and 7 describe the populations trends and demographics of affected species in relation to known longline fishing effort in the Southern Ocean and other possible environmental effects. Chapter 6 describes the long term population trends of four longline affected species, as well as short term changes in the species that is most frequently killed in all southern hemisphere longline fisheries, the white-chinned petrel *Procellaria aequinoctialis*. Chapter 7 analyses long term changes in the demographic parameters of wandering albatrosses breeding at Marion Island.

Finally, in the Conclusions and Synthesis I attempt to put in place all the links between the chapters and look at the work as a whole. A simple age-structured model is constructed for the Marion Island wandering albatross population in order explore the effects of our measured variables and give insight into the dynamics of this population and other seabird populations on Marion Island, affected by longline fishing. Directions for future research are also suggested.

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CHAPTER 1

Seabird mortality in the Patagonian toothfish longline fishery around the Prince Edward Islands, 1996-2000

ABSTRACT

Sanctioned longline fishing for Patagonian toothfish *Dissostichus eleginoides* around the Prince Edward Islands (a globally important seabird breeding site) commenced in 1996 following high levels of Illegal, Unregulated and Unreported (IUU) fishing. Independent fishery observers accompanied all but two sanctioned trips between 1996 and 2000, allowing a thorough understanding of the impact of this fishery on seabirds. Overall, white-chinned petrels *Procellaria aequinoctialis* were by far the most frequently killed species. However, during the first year, when lines were set during the day and night, a significant number of albatrosses (particularly grey-headed albatrosses *Thalassarche chrysostoma*) were also killed. Birds were caught almost exclusively during their breeding seasons and most birds killed were breeding adult males from the Prince Edward Islands. Albatrosses and giant petrels were caught almost exclusively during day sets, whereas catch rates of white-chinned petrels did not differ between day and night sets. Albatrosses were caught closer to the islands than white-chinned petrels. Most white-chinned petrel carcasses were hooked in their wings and bodies, whereas albatrosses were caught most frequently in their bills and contained large numbers of baits. Rates of seabird bycatch in the sanctioned fishery decreased from 0.19 birds/1000 hooks to 0.034 birds/1000 hooks during the time of this study. This was probably mainly due to stricter implementation of mitigation measures and a progressive shift in fishing effort away from the islands over the years. It is estimated that the combined impact of sanctioned and IUU longline fishing around the Prince Edward Islands over the past four years, could have resulted in between 8 500 and 18 500 seabird mortalities and could have had significant impacts on the breeding populations of several seabird species breeding on the Prince Edward Islands. This was mainly due to high levels of IUU fishing during 1996/97.

INTRODUCTION

Incidental mortality due to longline fishing practices is the principal threat to many species of albatrosses and petrels that are suffering global population decreases (Croxall & Gales 1998). The problem of incidental mortality was initially highlighted when Brothers (1991) observed Japanese longline fishing operations for tuna *Thunnus* spp. around Australia, and estimated that tens of thousands of albatrosses were killed annually throughout the Southern Ocean. Deaths of large numbers of albatrosses and petrels have since been documented in a range of longline fisheries operating both at a distance (Barnes *et al.* 1997, Gales *et al.* 1998, Ryan & Boix-Hinzen 1998) and close to the breeding islands of these birds (e.g. Cherel *et al.* 1996, Moreno *et al.* 1996, Weimerskirch *et al.* 2000).

Longline fishing for Patagonian toothfish *Dissostichus eleginoides* is a demersal fishery, generally restricted to slope areas surrounding South America, the sub-Antarctic islands and seamounts. This fishery has attracted much attention from conservationists, due to its close proximity to the breeding islands of threatened populations of albatrosses and petrels, as well as the high levels of Illegal, Unregulated and Unreported (IUU) fishing, presumably using few (if any) measures to reduce seabird mortality. The remote location of this fishery has made the regulation and control of IUU fishing very difficult, especially for a developing country such as South Africa, which has limited blue-water naval capacity.

Longline fishing for Patagonian toothfish in the sub-Antarctic first commenced during 1985/86 in the vicinity of South Georgia, in the Atlantic sector of the Southern Ocean, (Dalziell & De Poorter 1993) and was soon followed by fishing around Kerguelen, Indian sector, (Cherel *et al.* 1996) in 1990/91. Sanctioned longline fishing for Patagonian toothish within the 200 nautical mile Exclusive Economic Zone (EEZ) around South Africa's Prince Edward islands only commenced in October 1996, after considerable IUU fishing during the earlier part of the same year (Purves 1997). The Prince Edward islands are the breeding site of globally important populations of seabirds (Barnes & Huyser 1998, Williams *et al.* 1979). As part of their permit conditions, all sanctioned fishing vessels were required to carry independent scientific observers. This paper describes; 1) observed catch rates and estimated numbers of

birds killed, 2) characteristics of seabirds killed in terms of species, sex, age, and provenance, and 3) the temporal and spatial distribution in seabird bycatch.

METHODS

Twelve sanctioned fishing vessels undertook 52 fishing trips to the Prince Edward Islands EEZ between August 1996 and September 2000. All but one vessel used a single-line system with a Mustad autobaiter (Brothers *et al.* 1999). The remaining vessel used a hand baited, double-line (Spanish) system on 10 fishing trips (Brothers *et al.* 1999). Single lines set with a Mustad autobaiter (88% of sets) averaged 3 900 hooks (SD 2 400, range 1 000-20 000), with an average setting time of 23 minutes (SD 16 minutes). Spanish style double lines averaged 6300 hooks (SD 2 600, range 1 800-15 800), with an average setting time of 62 minutes (SD 26 minutes). From 1997 one vessel fished with an underwater setting funnel and was permitted to set lines during the day to test the efficacy of this mitigation measures. The results of this experiment are discussed in Ryan & Watkins (2002). Permit conditions followed CCAMLR Conservation Measure 29/XIX and include: 1) exclusive night setting (unless using an underwater funnel), 2) deployment of a bird scaring (*tori*) line, 3) no offal jettisoned during setting, 4) appropriate line weighting, and 5) offal to be jettisoned on the opposite side of the ship from the hauling station and not during setting.

Independent fishery observers were placed aboard 50 of the 52 fishing trips between the beginning of October 1996 and the end of September 2000. Because no independent assessment could be made of the numbers of birds reported killed on the two trips made without observers, these trips were excluded from analyses of bird bycatch. Observers recorded the position and time of the start and end of each set, the number of hooks set and the number and species of seabirds killed or injured during each set. Observers were given a brief training course on seabird identification prior to their first voyage and supplied with seabird identification material. Since 1999 observers were supplied with the Onley & Bartle (1999) identification booklet. The majority of observers did more than one trip and thus became proficient at seabird identification. The majority of seabird carcasses were returned to Cape Town, where their identification was verified. The sex and stomach contents of these carcasses were

also determined by means of biopsy. Only 7% of seabirds were not identified to species. These were almost all identified to the level of albatross, giant petrel or petrel. For the purposes of estimating total impacts on species we divided these unidentified birds according to the proportions of the species within each group, that were positively identified from carcasses. Observers were required to observe at least 50% of all hooks hauled (the balance of their time was spent recording fishery data). It is thus theoretically possible that the crew could dispose of birds when observers were not present, and that the reported bycatch rates are an underestimation. However, in general observers had a very good relationship with the crew and the observers were informed when birds were hauled aboard (BP Watkins pers. comm.). I am therefore confident that the disposal of bird carcasses by the crew did not occur on a scale that would significantly affect our results.

Annual data are given as split years, starting at the beginning of October (the month in which the first data were collected in 1996) and ending at the end of September the following year. This split not only gave four complete years of data, but also had the advantage of falling at the beginning of summer, when most seabirds start to breed and catch rates increase markedly. Data were analysed spatially using ARCVIEW Version 3.2 (ESRI, Redlands, USA). Distances were calculated using an Equidistant Azimuthal South Pole projection.

Estimates of IUU fishing effort within CCAMLR statistical area 58.7 (encompassing most of the fishing grounds within the South African EEZ) were taken from reports of the working group on fish stock assessment to CCAMLR (CCAMLR 1997, 1998, 1999, 2000). These estimates are calculated according to the following formula:

Effort (IUU) = Catch (IUU)/CPUE (Regulated fishery)
Where: CPUE = Catch Per Unit Effort

This figure was then extrapolated for entire Prince Edward Islands EEZ using the proportion of hooks set outside of CCAMLR statistical area 58.7 (but within the EEZ) by the sanctioned fishery. Because no information is available on seabird bycatch rates on IUU vessels, seabird bycatch rates from the 1996/97 sanctioned fishing season (when lines were set during the day and night; see Table 1.1) were used to

estimate the number of birds killed by IUU fishing. The mean seabird bycatch rate for all sanctioned vessels during the first year and the highest annual bycatch rate of a sanctioned vessel (that set an equal number of hooks in the summer and winter) during the first year, were used to calculate a range of estimates. The use of the highest bycatch rate from the sanctioned vessels is justified, as IUU vessels are under no obligation to use any mitigation measures and are thus likely to have considerably higher seabird bycatch rates than the sanctioned vessels (CCAMLR 2000).

RESULTS

Description of the fishery

Approximately 23 million hooks were set by sanctioned vessels between September 1996 and October 2000 (Table 1.1). During the first season approximately half of these hooks were set during the daylight hours, while in the subsequent seasons sets were mostly made during the night, due to strict enforcement of permit conditions. During 1997/98 and 1998/99, hooks set during daylight hours without a funnel constituted only 2% of all sets, but this increased to 10% during 1999/2000.

Fishing effort varied spatially between the seasons (Fig. 1.1). During the first year, most fishing effort was concentrated close to the islands. During the subsequent years fishing effort gradually moved farther away from the islands and more effort was concentrated on banks distant from the islands, but still shallower than 2000 m.

Species composition

A total of 1 761 birds were killed in the four years of sanctioned fishing operations, at an average rate of 0.08 birds/1000 hooks (Table 1.1). Of the 12 species of seabirds that were killed, white-chinned petrels were by far the most common (80% of all mortalities), followed by grey-headed albatrosses (7%) (Table 1.2). Albatrosses made up 12% of the total birds killed, but most of these were killed during the first year (22% of mortalities, compared with only 2% in all subsequent years; $\chi^2 = 163$, $P < 0.001$). Five macaroni penguins, which were all foul hooked in the body, were also amongst the mortalities.

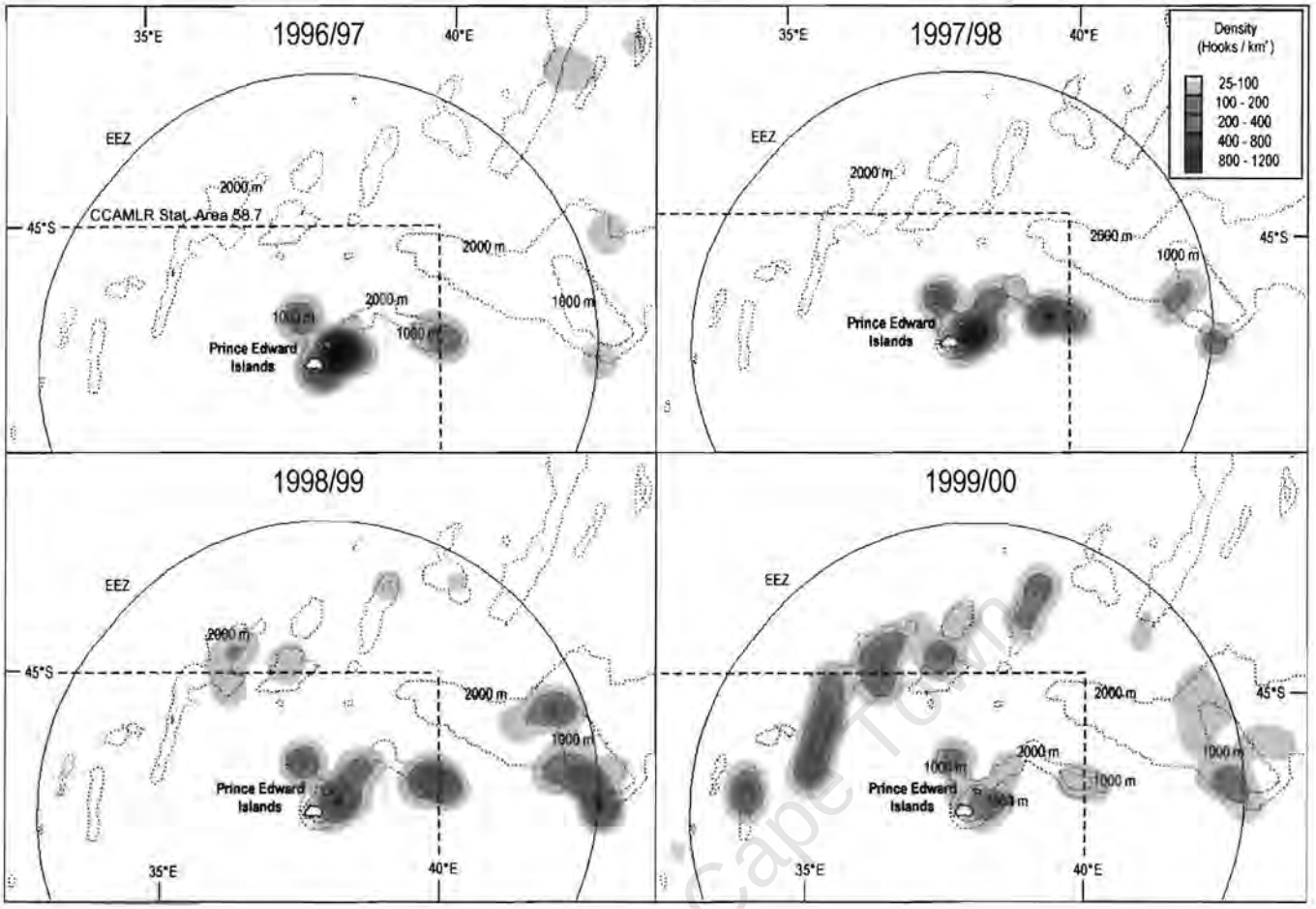

Figure 1.1 Density of hooks set in the longline fishery for Patagonian toothfish around the Prince Edward Islands (1996-2000), in relation to bathymetry.

Table 1.1 Number of hooks set and seabird bycatch rates by sanctioned longline vessels fishing for Patagonian toothfish in the Prince Edward Islands' EEZ, October 1996 to September 2000. Funnel = hooks set through an underwater setting funnel. Day = sunrise to sunset; Dusk = sunset to nautical twilight; Dawn = nautical twilight - sunriseto sunrise; Night = nautical twilight (evening) to nautical twilight (morning).

		Thousands of hooks set (% effort)				
Parameter		1996/97	1997/98	1998/1999	1999/2000	Total
Day	No funnel	2 024 (42%)	93 (2%)	138 (2%)	807 (10%)	3 062 (13%)
	Funnel	0	118 (2%)	369 (6%)	1 609 (21%)	2 096 (9%)
Dusk	No funnel	259 (5%)	632 (13%)	888 (15%)	1 272 (16%)	3 051 (13%)
	Funnel	0	9 (<1%)	106 (2%)	42 (<1%)	157 (7%)
Dawn	No funnel	274 (6%)	106 (2%)	124 (2%)	92 (1%)	596 (3%)
	Funnel	0	0	12 (<1%)	13 (<1%)	25 (<1%)
Night	No funnel	2 233 (47%)	3 780 (79%)	4 073 (69%)	3 830 (50%)	13 916 (60%)
	Funnel	0	36 (<1%)	202 (3%)	59 (<1%)	297 (1%)
Total hooks		4 790	4 774	5 912	7 724	23 201
Birds killed		911	497	91	262	1 761
Bycatch rates (birds/1000 hooks)		0.190	0.104	0.015	0.034	0.076

Table 1.2 Numbers of seabirds killed by sanctioned Patagonian toothfish longline vessels in the Prince Edward Islands EEZ, 1996-2000. These data exclude two fishing trips made during 1996, without fishery observers.

Species	1996/97	1997/98	1998/99	1999/00	Total (% of total)
White-chinned petrel *Procellaria aequinoctialis*	614	477	64	245	1 400 (80%)
Grey-headed albatross *Thalassarche chrysostoma*	126		1	3	130 (7%)
Indian yellow-nosed albatross *Thalassarche carteri*	31	2		9	42 (2%)
Unidentified giant petrels *Macronectes* spp.	6	12	8	1	27 (2%)
Southern giant petrel *Macronectes giganteus*	17		2		19 (1%)
Grey petrel *Procellaria cinerea*	1		13	2	16 (1%)
Northern giant petrel *Macronectes halli*	7	1	2	2	12 (1%)
Macaroni penguin *Eudyptes chrysolophus*		5			5 (<0.5%)
Black-browed albatross *Thalassarche melanophrys*	3				3 (<0.5%)
Sooty albatross *Phoebetria fusca*	1				1 (<0.5%)
Wandering albatross *Diomedea exulans*	1				1 (<0.5%)
Pintado petrel *Daption capense*			1		1 (<0.5%)
Sub-antarctic skua *Catharacta antarctica*	1				1 (<0.5%)
Unidentified petrels	54				54 (3%)
Unidentified albatrosses	37				37 (2%)
Unidentified birds	12				12 (1%)
Total	911	497	91	262	1 761

Seasonality, inter-annual variation and distance from the islands

Bycatch rates of seabirds were highest during 1996/97 (0.19 birds/1000 hooks), dropping to their lowest rate in 1998/99 (0.01 birds/1000 hooks) before increasing again slightly in 1999/2000 (Table 1.1). During 1996/97 most fishing effort was within 50 km of the islands and spread fairly evenly throughout the year (Fig. 1.2). Seabird bycatch rates were the highest during January and February and within 200 km of the islands, when 61% of birds were killed from only 9% of hooks set. During 1997/98 fishing effort started to become more dispersed, but 40% of effort during this year occurred within 200 km of the islands between January and March, resulting in 86% of bird mortalities. During the next two seasons, fishing effort moved farther from the islands. During 1998/99, substantial fishing effort close to the islands only occurred between August and October, while during 1999/00 most fishing effort occurred further that 200 km from the islands. Seabird bycatch rates were far lower during these years (Table 1.1). Interestingly, grey petrels did not conform to this trend, with more being caught in the last two years. The reasons for this are unknown.

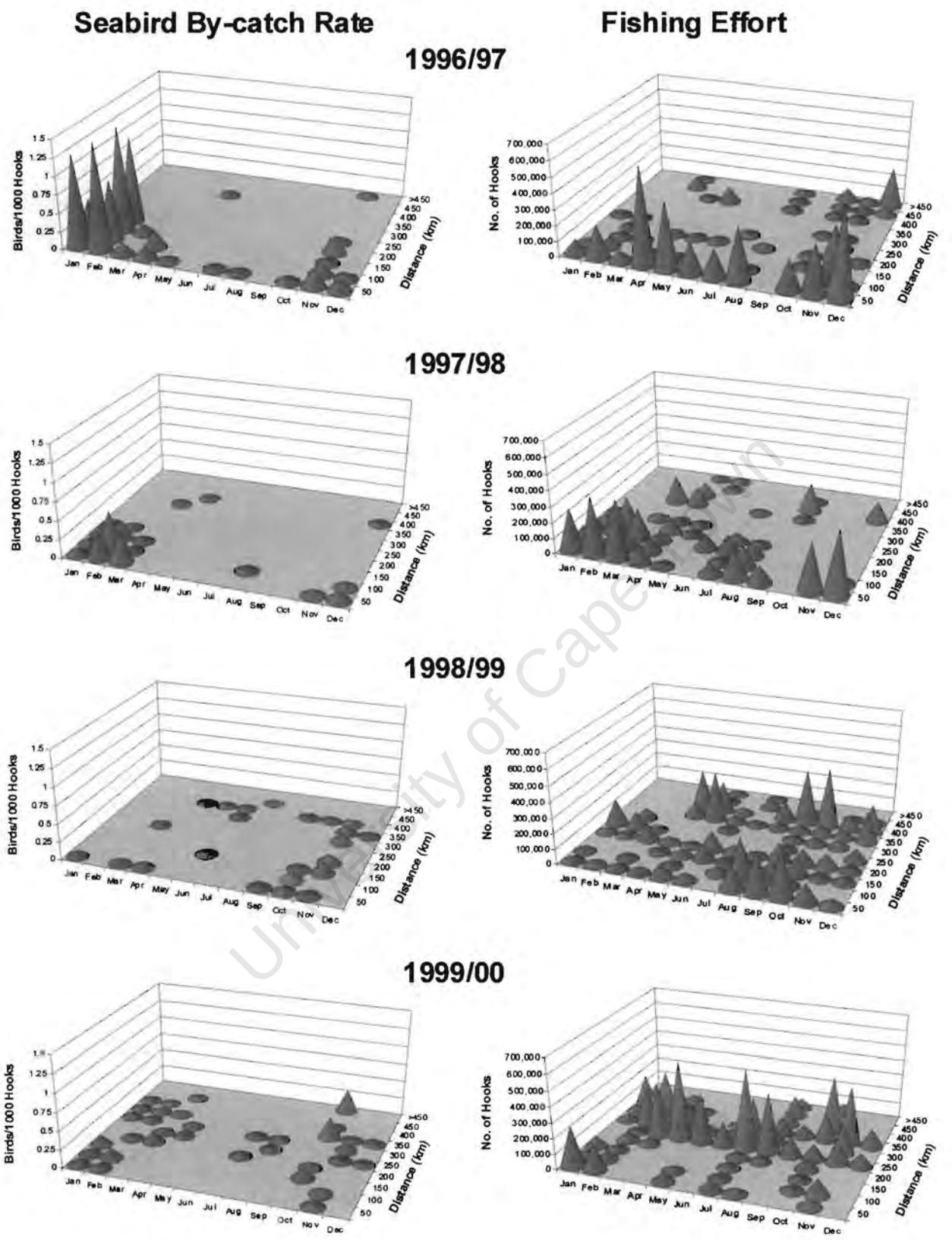

Figure 1.2 Seabird bycatch rates and longline fishing effort as functions of season and distance from the islands in the Patagonian toothfish longline fishery at the Prince Edward Islands

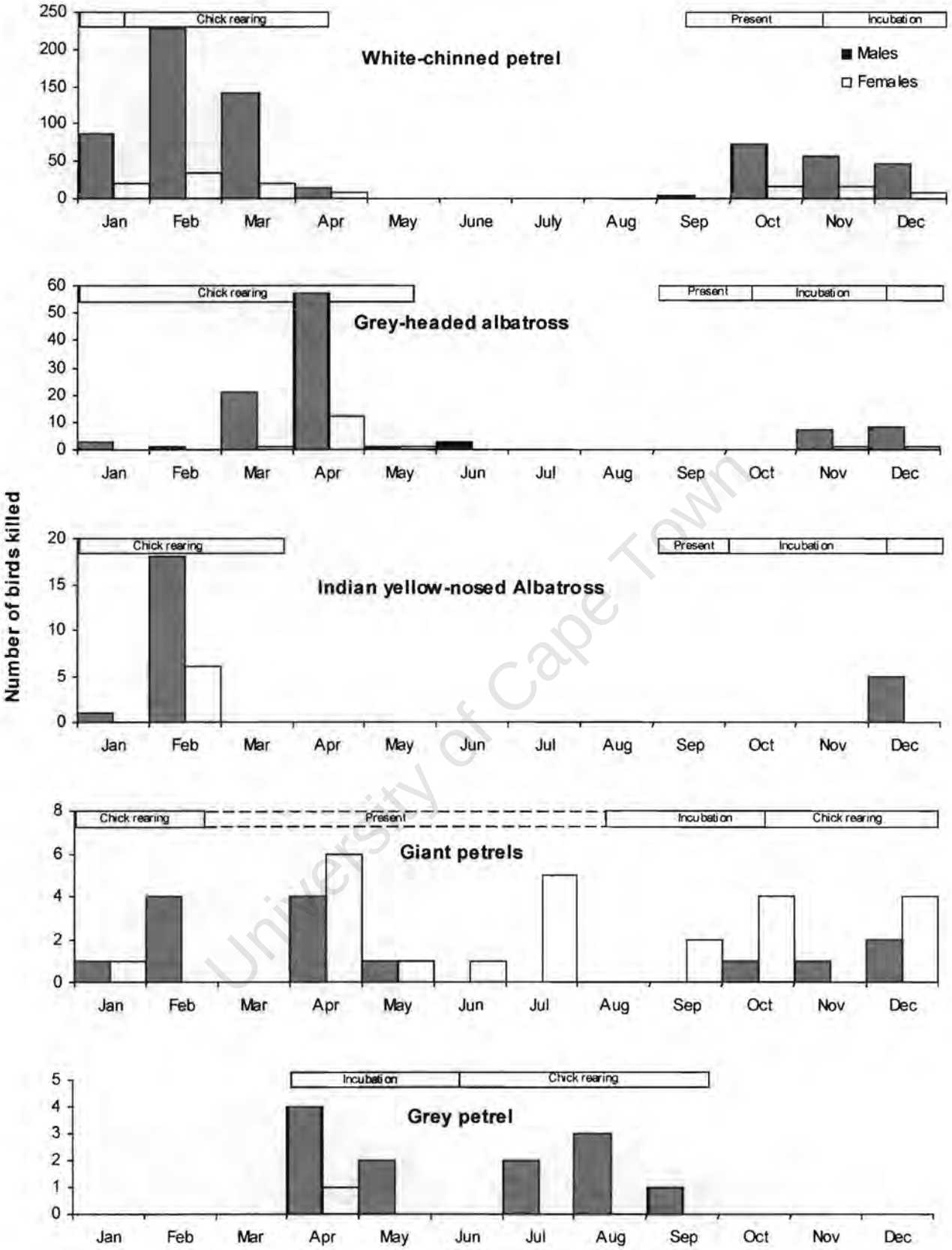

Figure 1.3 Seasonality in the mortality of seabirds in the longline fishery for Patagonian toothfish around the Prince Edward Islands, 1996-2000.

With the exception of giant petrels, mortalities of all species killed in substantial numbers occurred almost exclusively during their breeding season (Fig. 1.3). Mortalities of white-chinned petrels, grey-headed albatrosses and Indian yellow-nosed albatrosses were greatest when these species were rearing chicks. This was mainly due to a large increase in the number of males that were caught.

Differences in the distance from the islands at which mortalities occurred were analysed for daylight sets only (thus allowing equal probability of all affected species being killed) (Fig. 1.4). Almost all albatrosses and giant petrels (98%) and were caught within 200 km of the islands, whilst 85% of white-chinned petrels were caught within 200 km of the islands. High catch rates of albatross and giant petrels were restricted to within 100 km of the islands, whereas white-chinned petrel catch rates remained high up to 200 km from the islands. 94% of albatross and giant petrel mortalities occurred within 100 km of the islands, compared to 68% for white-chinned petrels ($\chi^2 = 22.7$; $P < 0.001$). In fact, 57% of all albatross and giant petrel mortalities occurred within 25 km of the islands.

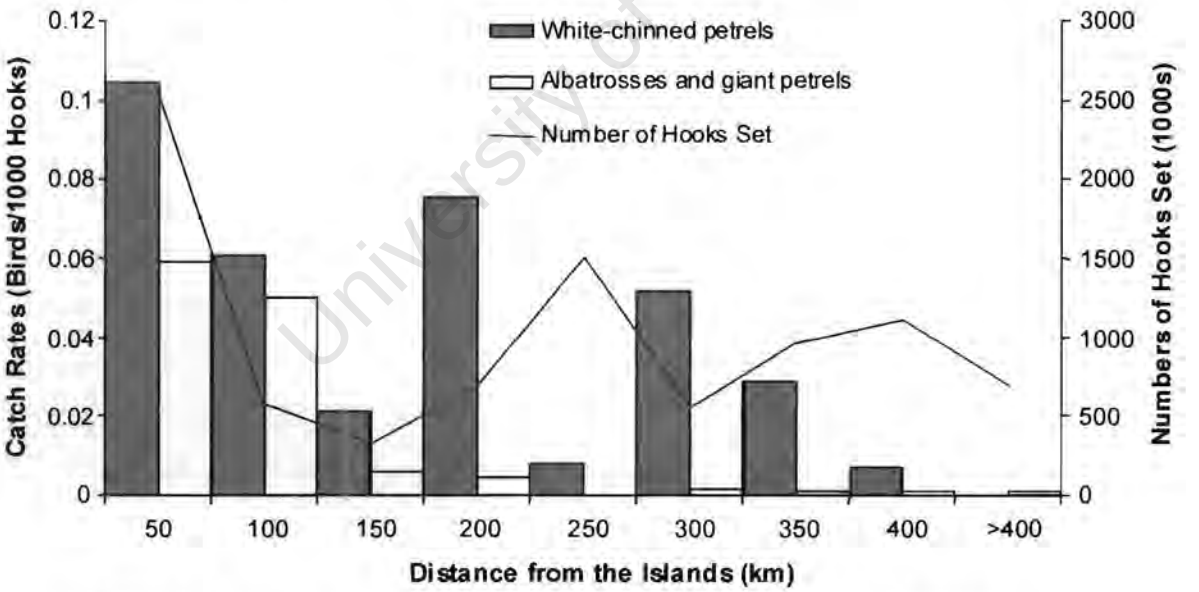

Figure 1.4 Seabird bycatch rates during daylight sets as a function of distance from the islands in the longline fishery for Patagonian toothfish around the Prince Edward Islands, 1996-2000.

Sex, age, breeding status and provenance of dead birds

Males made up more than 80% of the carcasses of white-chinned petrels, grey-headed albatrosses, yellow-nosed albatrosses and grey petrels that were examined (Table 1.3). Giant petrels were a notable exception, with only 37% of the carcasses being male. Male biased mortality of white-chinned petrels was significantly higher during the chick-rearing season (87%) than during the rest of the season (78%) ($\chi^2_1 = 6.28$; $P = 0.012$). On average, male white-chinned petrel mortalities occurred closer to the islands than females ($U = 24610$; $P = 0.006$; df = 740). Male-biased mortality was also higher within 200km of the islands (85%) than further away (78%), although this was not quite significant ($\chi^2 = 3.46$; $P = 0.063$).

Table 1.3 Proportion of male seabirds killed by sanctioned Patagonian toothfish longline fishing vessels in the Prince Edward Islands EEZ, 1996-2000, based on carcasses returned to Cape Town.

Species	% Adult	% Male	*n*	*P* (sex ratio)
White-chinned petrel	-	84.1	790	<0.001
Grey-headed albatross	99	86.4	118	<0.001
Yellow-nosed albatross	100	80.6	31	<0.005
Giant petrels	97	36.8	38	ns
Grey petrel	-	87.5	16	<0.01

ns = $P > 0.05$

Almost all birds killed were in adult plumage. Only two immature albatrosses were caught: one grey-headed albatross (caught in April – at the end of the breeding season) and one black-browed albatross (a species that does not breed on Marion). One white-chinned petrel still had some down on its head, and had just fledged; it was caught during the main fledging period of white-chinned petrels on Marion (April). One southern giant petrel in immature plumage was killed during the non-breeding season. This bird had been banded as a chick and was seven years old. Of white-chinned petrels killed during December and January (peak incubation for white-chinned petrels on Marion Island), 87% had well-developed brood patches (n = 75 birds examined).

Twelve banded birds were reported killed by sanctioned fishing vessels: seven northern giant petrels, three southern giant petrels and two white-chinned petrels. All

but one had been banded on Marion Island. The exception was a white-chinned petrel banded on the nearby Crozet Islands. This bird, a non-breeding juvenile approximately 2 years old, was caught 34 km from the Prince Edward Islands. Two of the giant petrels had been banded as fledglings while the remainder had been banded as breeding adults. The average minimum age was calculated by adding the average age of first breeding (for the relevant species – Marchant and Higgins 1990) for birds that were banded as breeding adults. The average minimum age of the seven northern giant petrels was 16 years (range 10 – 21 years), and 18 years for the three southern giant petrels (range 7 – 29 years). The white-chinned petrel banded on Marion Island was a minimum of 23 years old.

Time of Day

Seabird mortality rates were significantly higher for lines set during the day (0.106 birds/1000 hooks) than those set at night (0.073 birds/1000 hooks) ($\chi^2 = 57.6$; $P < 0.001$). However, this was due the large difference in mortality rates of albatrosses and giant petrels during the day (0.031 birds/1000 hooks) compared to the night (0.004 birds/1000 hooks) ($\chi^2 = 253$; $P << 0.001$) (Fig. 1.5). There was no difference in the mortality rates of white-chinned petrels during the night and the day ($\chi^2 = 1.57$; $P = 0.2$) (Fig 1.5).

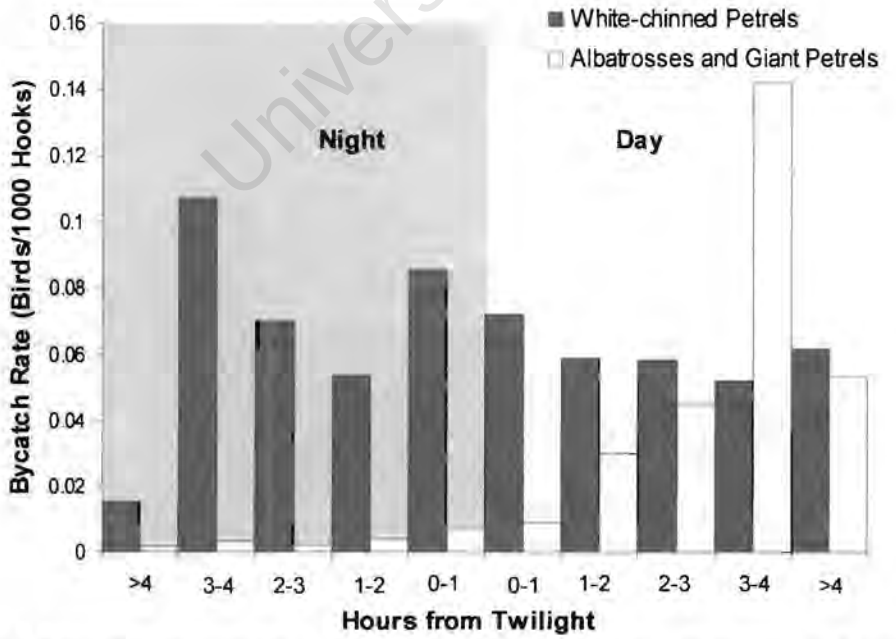

Figure 1.5 Incidental mortality rates of white-chinned petrels, albatrosses and giant petrels in relation to daylight in the longline fishery for Patagonian toothfish around the Prince Edward Islands, 1996-2001

Mortality rates of albatrosses were highest during daylight, 3 - 4 hours from twilight, whereas mortality rates of white-chinned petrels were highest during the night, with a slight peak at about 4 hours from twilight (Fig. 1.5).

Hooking position and stomach contents

Upon examination, 619 carcasses still had hooks embedded in them. Albatrosses were caught most frequently in their bills (63% of 114 carcasses), whereas white-chinned petrels were caught most frequently in their wings or body (76% of 505 carcasses). The proportion of white-chinned petrels caught in their bills (24%) was significantly less than albatrosses (63%; $\chi^2_1 = 66$; $P < 0.001$).

A total of 73% of grey-headed albatross carcasses contained bait pieces (Table 1.4). One grey-headed albatross contained 16 pieces of bait, with 9% containing 10 or more pieces. Approximately half of Indian yellow-nosed albatross and giant petrel carcasses contained baits, whereas only 19% of white-chinned petrel carcasses contained baits. Of the 571 bait pieces found in these seabird carcasses, 93% were fish bait, while the rest were squid. This is significantly different from the proportion of hooks that were set with fish bait (only 67%) ($\chi^2 = 177$; $P < 0.001$). Toothfish remains and other offal were found most frequently in giant petrel carcasses (30%), followed by grey-headed albatrosses (23%). Only 4% of white-chinned petrels contained offal remains. An old toothfish hook was found in a grey-headed albatross, as well as a white-chinned petrel.

Total numbers of seabirds killed

In addition to the 23 million hooks set by the sanctioned fishery, an estimated 35 million hooks were set by IUU fishing vessels (Table 1.5). This estimate is crude and is likely to be an underestimate. Most IUU effort took place during the first season (1996/97) when an estimated 25 million hooks were set. IUU fishing effort decreased during the following two seasons, but showed signs of increasing again during 1999/2000. Little data exist on the spatial distribution of IUU fishing, but IUU vessels were regularly sighted from the island during the second half of 1996 and during 1997. Extrapolation using bycatch rates recorded during the first year of sanctioned fishing (when lines were set during day and night), suggests that between 7000 and

17000 birds could have been killed by IUU fishing around the Prince Edward Islands EEZ between 1996-2000 (Table 1.5). The majority of these birds would have been killed during the first season (1996/97), when most IUU fishing occurred. It is estimated that in total between 8 500 and 18 500 birds were killed in both sanctioned and IUU fishing for Patagonian toothfish around the Prince Edward Islands between 1996-2000 (Table 1.6).

Table 1.4 Stomach contents of seabirds killed by sanctioned Patagonian toothfish longline vessels in the Prince Edward Islands EEZ, 1996-2000.

	White-chinned petrels (n = 790)	Grey-headed albatrosses (n = 118)	Yellow-nosed albatrosses (n = 31)	Giant petrels (n = 30)
% Birds containing:				
>10 baits	0%	8.5%	0%	0%
5-10 baits	0.9%	15.3%	9.7%	3.3%
2-5 baits	7.2%	33.9%	25.8%	20%
1 Bait	10.6%	15.3%	16.1%	26.7%
Total containing baits	18.7%	72.9%	51.6%	50%
Toothfish & offal	4.4%	22.9%	3.2%	30%
Toothfish hooks	0.1%	0.8%	0%	0%

Table 1.5 Estimated IUU longline fishing effort for Patagonian toothfish and estimated seabird mortalities within the Prince Edward Islands EEZ, 1996-2000.

IUU Parameter	1996/97	1997/98	1998/99	1999/00	Total
Estimated number of hooks set in area 58.7 (millions) [1]	20.8	4.6	1.4	2	28.8
Estimated number of hooks set within the PEI EEZ (millions) [2]	25.2	5.6	2.2	2.4	35.4
Estimated number of birds killed within the PEI EEZ by IUU fishing [3] (1000s)	4.8–11.8	1.1–2.6	0.4–1.0	0.5–1.1	6.8–16.7

[1] From reports of the working group on fish stock assessment to CCAMLR (CCAMLR 1997, 1998, 1999, 2000)
[2] Extrapolated using the proportion of hooks set outside CCAMLR statistical area 58.7 (but within the PEI EEZ) by the sanctioned fishery for each year
[3] Calculated using the average bird bycatch rate for all sanctioned vessels during the 1996/97 season (0.19 birds/1000 hooks) as well as the bycatch rate of the vessel with the highest bycatch rate for year (with equal effort in summer and winter; 0.47 birds/1000 hooks)

Table 1.6 Estimated numbers of total number of seabirds killed by sanctioned and IUU longline fishing for Patagonian toothfish within the Prince Edward Islands EEZ, 1996-2000.

Species	Sanctioned vessels	IUU vessels	Total	% Prince Edward Islands breeding population[1]
White-chinned petrel	1 450	5 000 – 12 300	6 500 – 14 000	8 - 18%[2]
Grey-headed albatross	150	1 000 – 2 500	1 150 – 2 650	5 - 12%
Yellow-nosed albatross	70	450 – 1 107	510 – 1 180	3 - 7%
Southern giant petrel	36	160 – 390	200 - 430	4 - 10%
Northern giant petrel	22	70 – 170	90 - 190	7 - 16%
Grey petrel	14	70 – 170	80 - 180	1 - 5%[2]
Black-browed albatross	3	20 – 50	20 – 50	Non-breeder
Sooty albatross	1	10 – 25	10 – 25	<<1%
Wandering albatross	1	10 – 25	10 – 25	<<1%
Sub-antarctic skua	1	10 - 25	10 - 25	ca. 1%
Total	1 754	6 800 – 16 700	8 554 – 18 450	

[1] Calculated from best available population data (unpubl. data from the FitzPatrick Institute, University of Cape Town and the Department of Marine and Coastal Management, South Africa).
[2] Population estimates of these burrow nesting species are not accurate.

DISCUSSION

Seabird bycatch rate in sanctioned longline fishing for Patagonian toothfish around Marion Island has been characterised by considerable inter-annual variation. Seabird bycatch rates were greatest when fishing effort was concentrated close to the islands and equally distributed between the day and night sets. When fishing effort moved farther away from the islands and line setting was restricted to the night only, bycatch rates dropped by an order of magnitude.

The species composition of the seabird bycatch at the Prince Edward Islands showed certain similarities to, but other distinct differences from Patagonian toothfish longlining operations at other localities (Table 1.7). White-chinned petrels are the most frequently killed seabird species in Patagonian toothfish longlining operations at all localities. However, grey-headed albatrosses are killed in moderate numbers at the Prince Edward Islands and around Kerguelen, but suffer lower mortality rates around South Georgia. Giant petrels, are caught in significant numbers in toothfish longline operations around the Prince Edward Islands and South Georgia, but in four seasons

Table 1.7 Comparative species specific bycatch rates for longline fisheries for Patagonian toothfish at different localities, when lines were set throughout the year (i.e. before seasonal closures).

Species	Prince Edward Islands Average (annual range)	South Georgia[1]	Kerguelen[2]
White-chinned petrel	0.06 (0.011-0.139)	0.208	0.59
Grey-headed albatross	0.007 (0-0.0327)	0.0018	0.018
Indian yellow-nosed albatross	0.002 (0-0.0079)	0	0
Southern giant petrel	0.002 (0-0.004)	0.029	0
Northern giant petrel	0.0009 (0-0.002)	0.0009	0
Black-browed albatross	0.0001 (0-0.0006)	0.022	0.022
Wandering albatross	0.00004 (0-0.0002)	0.005	0.007
Total	0.076 (0.015 – 0.190)	0.268	0.590

[1] Moreno *et al.* (1996) These data refer to the 1995 season when lines were set throughout the year (i.e. comparable to the data presented for the Prince Edward Islands). A restricted season has since lowered bycatch rates at South Georgia by two orders of magnitude (CCAMLR 2000).
[2] Weimerskirch *et al.* (2000)

of fishing around Kerguelen, not a single giant petrel was killed, despite large numbers being present around longliners in this area (Weimerskirch *et al.* 2000). Wandering albatrosses are killed in significant numbers in toothfish longline operations around both South Georgia and Kerguelen, but only a single wandering albatross was killed in four years of sanctioned fishing around the Prince Edward Islands. Finally, black-browed albatrosses, which do not breed at the Prince Edward Islands, suffer much higher mortality rates at their breeding islands of Kerguelen and South Georgia. It is therefore clear that impacts on species vary between islands, and that broadscale interpolations between geographic localities can be misleading. These differences probably result from differences in the species composition and subsequent dominance hierarchies at fishing vessels, as well as local foraging conditions.

Night-setting is the most effective means of reducing albatross and giant petrel mortalities. However, white-chinned petrel mortality rates did not differ between day and night. This is in contrast to results from Kerguelen, where mortality rates of white-chinned petrels were significantly higher during the day (Weimerskirch *et al.* 2000). Interestingly, bycatch rates of white-chinned petrels peaked 3-4 hours before dawn or after dusk. Barnes *et al.* (1997) reported that white-chinned petrel activity at

longline vessels targeting hake *Merluccius* spp. off South Africa was greater 2-3 hours before dawn and after dusk, compared to the middle of the night. Although night-setting did not effectively reduce catch rates of white-chinned petrels at the Prince Edward Islands, this mitigation method should be retained due to its effective reduction of albatross and giant petrel catch-rates. Most albatrosses and giant petrels have relatively small global populations and any mitigation method that effectively reduces the impacts to these populations should be retained. Further research into methods that effectively reduce catch-rates of nocturnal foraging seabirds such as white-chinned petrels is needed, as well as the more widespread use of methods that have been shown to effectively reduce catch rates (e.g. the use of under-water setting devices; Ryan & Watkins 2002).

With the exception of giant petrels, most birds were caught during their breeding seasons, with the highest catch rates occurring during the chick rearing period. Several studies have shown that albatrosses and petrels reduce their foraging range during the chick rearing period, due to the constraints of needing to feed a chick at frequent intervals (e.g. Berrows *et al.* 2000, Weimerskirch *et al.* 1993, Chapters 3 & 4). This causes their main foraging areas to overlap more with the toothfish fishing grounds. Closing the fishery during the major part of the chick rearing period of white-chinned petrels (January to March) will be the most effective way of reducing the mortality of this species. The fishery around South Georgia is closed from 1 September to 30 April in order to reduce the incidental bycatch of seabirds (CCAMLR 2000). Ideally a similar restriction should be in place at the Prince Edward Islands, however, due to the high incidence of IUU fishing around the Prince Edward Islands and the lack of political will by the South African government to police these waters, fisheries management authorities decided that it was preferable to have sanctioned fishing vessels operating in these waters than no presence at all. As seabird bycatch rates were much higher within 200 km of the islands, it may be feasible to only reduce the fishing effort within 200 km of the islands for three months (January to March). However, a pre-requisite for such a mitigation measure, would be the availability of an effective means of monitoring and policing these waters for IUU vessels.

Judging from their stomach contents, grey-headed albatrosses appeared to be most proficient at successfully snatching baits. Surprisingly few white-chinned petrel carcasses contained baits, considering their high catch rates. The high proportion of white-chinned petrels foul-hooked in their wings and bodies, suggests that they are probably hooked by hooks that are flailing around in the air (close the stern of the vessel) or moving through the water column at a considerable rate. Lines are pulled taught and forwards through the water for several reasons. These include; 1) when the vessel is steaming too fast while setting, 2) when the line becomes entangled with a fixed structure on the vessel, 3) when the vessel is pitching severely in a heavy sea, 4) when the vessel is setting into a strong wind or current. Albatrosses were caught most frequently in their bills, probably while they were attempting to snatch baits.

Baits are obtained in three possible ways, they are either; 1) stolen from baited hooks as they enter the water (Brothers 1991), 2) obtained when baits are lost from hooks during the baiting and casting process or 3) scavenged when excess bait is disposed of after the set is complete. The higher proportion of fish bait found in the seabird casualties compared to that used by vessels suggests that birds are more successful at removing fish bait from hooks, or that there is higher loss of fish baits during setting (possibly due to the softer flesh of fish). Bait loss to seabirds reduces the efficiency of fishing operations. It should thus be in the economic interest of fishers to reduce the access of seabirds to baited hooks as they enter the water. I encourage measures to reduce bait wastage (by increasing baiting efficiency and the retention of excess baits) at the stern of the vessel, as this increases the attractiveness of this site to seabirds.

Giant petrels contained the highest incidence of discards and offal obtained from scavenging around the offal chute, indicating their dominance during this activity. It is also interesting to note that the single wandering albatross killed contained two toothfish heads. Wandering albatrosses breeding on the Prince Edward Islands during 1997 fed their chicks substantial amounts of offal from toothfish longline vessels (Chapter 3). This included toothfish heads, bycatch species as well as substantial amounts of fishing gear (including toothfish hooks and pieces of rope). Minimising the amount of easily available offal reduces the number of birds attending these vessels (Weimerskirch *et al.* 2000) and thus the number of birds at risk of being caught. This will also reduce the amount deleterious marine debris (such as hooks and

pieces of rope) being fed to chicks on the islands, which can lead to their death (Chapter 2).

One of the most important results of this study was to confirm the strong bias in mortalities of adult, breeding, males reported by Ryan & Boix-Hinzen (1999) after the first year of fishing. Several tracking studies of larger albatrosses have shown that males tended to forage closer to their breeding colonies during the breeding season and feed their chicks more frequently (Prince *et al.* 1998, Weimerskirch *et al.* 1997a, Chapters 3 & 4). This exposes males to a higher risk of being killed in Patagonian toothfish longline operations that are concentrated around their breeding islands. The two giant petrels were the only species caught in significant numbers that did not display a male bias. Both are opportunistic predator-scavengers on their breeding islands (Hunter & Brooke 1992). Male giant petrels show a higher reliance on penguin and seal carrion scavenged on the islands, while females feed more extensively on marine prey (Hunter & Brooke 1992, González-Solís *et al.* 2000). These differences probably account for the observed sex ratio. Grey petrels killed in the Japanese tuna fishery in New Zealand and Australian waters were almost all adult females caught during the winter (their breeding season) (Murray *et al.* 1993; Gales *et al.* 1998), suggesting a strong sexual segregation in foraging areas for adults of this species during their breeding season. The strong bias towards adult, breeding males observed in our study will exacerbate the impacts of this fishery on the populations breeding on the Prince Edward Islands. Albatrosses and petrels are extreme k-selected species, displaying high adult survival rates, delayed onset of first breeding and low reproductive rates (Warham 1996). While being more tolerant to perturbations to breeding success and juvenile survival, these populations are especially vulnerable to increased adult mortality (Croxall *et al.* 1990, Weimerskirch *et al.* 1997b). All affected albatross and petrel species are monogamous and successful reproduction typically requires well-established pairings (Marchant and Higgins 1990). For wandering albatrosses, loss of a mate reduces the life-time reproductive potential by up to 15% (Jouventin *et al.* 1999). A large sex-biased mortality will result in a surfeit of breeding adults of one sex, which will be redundant to the breeding population.

The sanctioned fishery around the Prince Edward Islands has effectively reduced its seabird bycatch through stringent implementation of mitigation measures. However

catch rates are still far higher than areas where seasonal closures occur (e.g. South Georgia; CCAMLR 2000). However, the major concern for the Prince Edward Islands fishery is the high levels of IUU fishing effort (especially during 1996/97), which probably killed between four and ten times as many birds as the sanctioned fishery. As most of these birds would have been adult breeding birds from Marion Island, significant proportions of the breeding populations of white-chinned petrels (8-18%), northern giant petrels (7-16%), grey-headed albatrosses (5-12%), southern giant petrels (4-10%), and yellow-nosed albatrosses (3-7%) could have been killed. It should be emphasized that these are conservative estimates as catch rates on IUU vessels are likely to have been far higher than on sanctioned vessels. Also, recent reports based purely on trade statistics suggest that CCAMLR estimates of IUU fishing effort may be considerable underestimates (Lack & Sant 2001). Although it is still too early to assess the full extent of this impact, annual counts of white-chinned petrels and giant petrels on Marion Island suggest that they have suffered recent decreases in numbers (Chapter 6). No short-term trend in grey-headed albatross numbers has been detected due to the large inter-annual variation in breeding numbers characteristic of this species (Chapter 6).

Seabird mortality in longline fisheries is a global problem (Brothers *et al.* 1999). Seabirds, and albatrosses and petrels in particular, are being killed in unsustainable numbers in longline fisheries in every major ocean. The management of the sanctioned fishery for Patagonian toothfish and the associated reduction in seabird by-catch in this fishery over the four years of this study can serve as a model for other fisheries. However, the lack of political will to deal with the IUU fishing problem in these waters (as in many other parts of the world) has largely negated these efforts. I encourage a more pro-active role by governments and Regional Fisheries Management Organisations (RFMOs) in tackling this problem, and support initiatives, such as the toothfish Catch Documentation Scheme (CDS), that have been set in place to minimise the sale of IUU catches. Furthermore, I encourage co-operation between governments (through the medium of international agreements) in dealing with IUU fishing problems around the islands located in the Southern Ocean, as well as at a global scale.

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CHAPTER 2

Marine debris and fishing gear associated with seabirds at sub-Antarctic Marion Island: changes in relation to longline fishing activity

ABSTRACT

This chapter reports on the marine debris found in association with seabirds at sub-Antarctic Marion Island for the period May 1996 to April 1998. The proportion of fishing gear to 'other' (non-fishing) marine debris found in association with seabirds more than doubled from the 1996/97 to the 1997/98 season. Sixty "rope nooses" (apparently used for suspending Patagonian toothfish in blastfreezers) and 23 toothfish hooks were found. Prior to this study only three hooks (all tuna longline hooks) had been found in association with seabird nests at Marion Island. Fisheries derived marine debris were found most frequently in association with wandering albatross nests, while 'other' marine debris was found most frequently in association with grey-headed albatrosses and southern giant petrels, indicating that larger species may be may be dominant in scavenging for offal around fishing vessels due to their physical size and ability to ingest large pieces of offal. Standardised searches of wandering albatross nests showed a threefold increase in fishing gear between the 1996/97 and the 1997/98 field seasons, whereas the occurrence of 'other' marine debris remained constant. Three seabirds (a southern giant petrel, a northern giant petrel, and a sub-Antarctic skua) were found entangled in fishing gear, while five seabird carcasses (three wandering albatross chicks, one white-chinned petrel chick and a southern giant petrel adult) were found to contain ingested fishing gear.

INTRODUCTION

Anthropogenic items, floating at the surface of the sea, are frequently ingested by certain species of seabirds. Albatrosses and petrels, because of their habits of feeding close to the sea surface and scavenging behind vessels, are particularly prone to ingesting large volumes of marine debris (Ryan 1987, Auman *et al.* 1998). Sampling marine debris found in association with these seabirds at their breeding colonies is a non-destructive technique that can provide us with much-needed information about the amount and type of marine debris available within their foraging ranges, as well as the level of interaction between these species and sources of marine debris (e.g. unregulated fishing vessels).

The interaction of procellariiforms with longline fishing vessels has been well documented (e.g. Brothers 1991, Cherel & Weimerskirch 1996, Chapter 1), and the global population declines of several species of albatrosses have been largely attributed to the incidental mortality caused by this fishing practise (Croxall & Gales 1998). Less well documented is the scale and effect that marine debris, obtained on the open ocean or from waste jettisoned by fishing vessels, may be having on populations.

The pelagic tuna *Thunnus* spp. longline fishery in the southern Indian Ocean peaked in the mid 1980s and has since decreased during the early 1990s (Polacheck & Tuck 1995, Weimerskirch *et al.* 1997). However, the development of a new longline fishing for Patagonian toothfish *Dissostichus eleginoides* on the shelf areas surrounding certain sub-Antarctic islands during the early to mid 1990s, has raised cause for concern (e.g. Ashford *et al.* 1995, Croxall & Prince 1996). Sanctioned longline fishing for Patagonian toothfish within the 200 nautical mile Economic Exclusive Zone (EEZ) around Marion Island (46°55'S, 37°45'E), began during the spring of 1996 (Chapter 1) following large scale Illegal, Unregulated and Unreported (IUU) fishing during the months prior to this.

This paper reports on marine debris and fishing gear found in association with seabirds on Marion Island during the period May 1996 to April 1998. Historic trends of longline fishing hooks found in wandering albatross *Diomedea exulans* study colonies during standardised nest checks are also compared.

METHODS

Marine debris was collected and recorded both incidentally and by means of standardised searches on Marion Island during period May 1996 to April 1998. Debris was found next to nests or within colonies, either as individual items or as part of a pellet of indigestible prey remains which had been regurgitated. In order to analyse trends the data has been divided into the two field seasons: May 1996 to the end of April 1997 (hereafter referred to as 96/97), and May 1997 to the end of April 1998 (referred to as 97/98).

By the term marine debris we refer exclusively to items that are of anthropogenic origin. The origin of fisheries derived items were ascertained through communication with scientific observers aboard sanctioned toothfish longline fishing vessels and inspection of vessels operating from Cape Town, South Africa. Toothfish hooks are easily distinguished from tuna hooks by their size and shape (Figure 2.1).

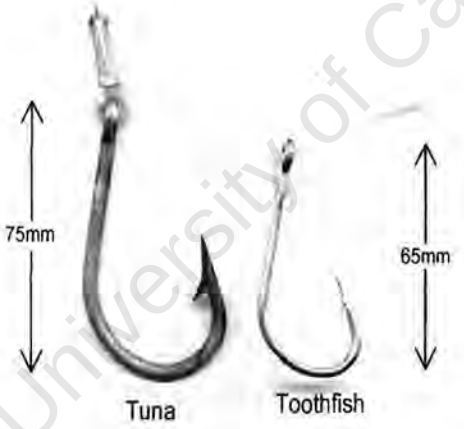

Figure 2.1 Tuna and Toothfish longline hooks.

Incidental finds

All marine debris found next to seabird nests or within colonies by field biologists during their normal work routine were collected and recorded. As we consistently collected all marine debris found, I do not expect that there will be any bias in the proportions of the types of debris collected (i.e. the proportion of fisheries derived items to non-fisheries derived items). It should be noted that the work routines during the two field seasons were similar, and therefore search effort was comparable.

Standardised searches of wandering albatross nests

Three wandering albatross long term monitoring colonies on the north eastern side of the island were checked at 10-day intervals between December (egg laying) and April (end of brood phase) and at monthly intervals between May and November/December (chick feldging). This method has been standardised since 1987. From April 1996 all nests in the colonies were actively searched for marine debris during each check. Prior to 1996, field workers did not actively search for marine debris, however obvious large marine debris such as fishing hooks with line attached would have almost certainly been spotted and recorded (pers. comms. from previous field ornithologists based on Marion Island). I also conducted the ornithological fieldwork during the 93/94 season and certainly would have noted any large marine debris (such as hooks) within these colonies.

All wandering albatross nests on Marion Island were searched for marine debris during a whole-island census during early incubation, January 1998. The monitoring colonies were excluded from this survey.

Entanglements and marine debris in carcasses

Incidents of seabirds entangled in marine debris were recorded and all fresh carcasses were dissected and inspected for debris.

RESULTS

Incidental finds

A total of 264 items of marine debris was found in association with seabird nests at Marion Island during this study (Appendix 1), of which most (80%) were found during the 97/98 field season. This was mostly due to an almost ten-fold increase in items originating from the fishing industry. Other (non-fishing) items doubled over the same time period. The proportion of debris originating from the fishing industry increased from 22% in 96/97 to 54% during the 97/98 season. The most numerous single item was a "rope noose", all of which (n = 60) were from the 97/98 season. These "rope nooses" are pieces of rope (of varying colour) which are all knotted in an identical manner (Fig. 2.2). Initial enquiries revealed that they were used for hanging fish in the blast freezers of certain toothfish longline vessels (R. Wanless and M. Purves pers. comm.). Nineteen of the 23 toothfish longline hooks were collected during the

97/98 field season. Only three hooks have previously been found in association with seabirds on Marion Island, all of which were tuna longline hooks found in association with wandering albatrosses.

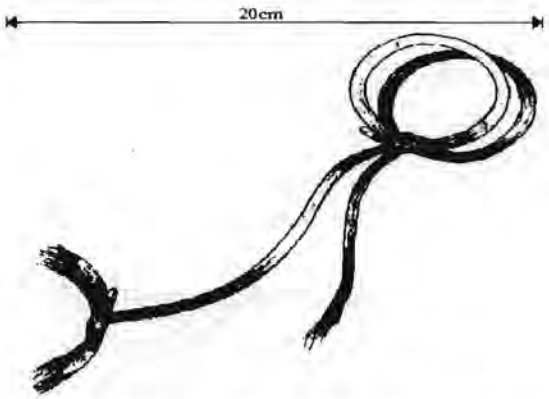

Figure 2.2 An illustration of a "rope noose", as frequently found in association with seabird nests on Marion Island during the 1997/98 season

Most items of marine debris were found in association with wandering albatross (n = 102), grey-headed albatross *Thalassarche chrysostoma* (n = 72) and southern giant petrel *Macronectus giganteus* (n = 69) and nests (Appendix 1.1). The proportion of fisheries-derived marine debris to "other" (non-fishing) marine debris varied greatly between these three species (Fig. 2.2). More than three quarters of the marine debris (78%) found next to wandering albatross nests was fishing gear, while only 32% of southern giant petrel, and 24% of grey-headed albatross nest debris originated from the fishing industry.

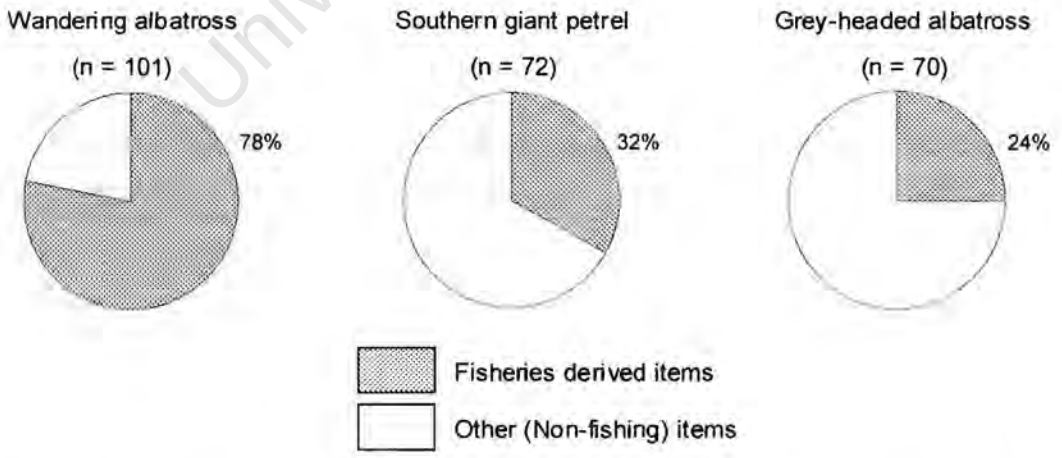

Figure 2.3 The proportion of fisheries-derived marine debris to "other" (non-fishing) marine debris for the three seabird species with the highest accumulation rates at Marion Island.

Standardised checks of wandering albatross nests

Of the 55 items collected in the three wandering albatross monitoring colonies during standardised checks, most (69%) was fishing gear. The number of items collected per 100 nests more than doubled from the 1997 to the 1998 season, and was mostly due to a three-fold increase in the amount of fishing gear, whereas the amount of "other" (non-fishing) items remained relatively unchanged (Table 2.1). The proportion of debris originating from the fishing industry increased from 53% during 96/97 to 75% during the 97/98 season. The 30 items of fishing gear collected during the 97/98 season were collected at 25 separate nests.

All 18 hooks found in this study were from Patagonian toothfish longline operations. In three instances two hooks were found next to the same nest and in these cases, one hook appeared more degraded than the other. Prior to this study, only one hook was found in these monitoring colonies since 1987. This was a tuna longline hook, which was found lodged in the neck of an incubating female during January 1996 (D. Keith pers. comm.).

Table 2.1 Marine debris found next in wandering albatross study colonies on Marion Island during standardised checks from May 1996 to April 1998.

Season (number of nests in colonies)	1996/97 (n=263)	1997/98 (n=290)
Hooks and snoods*	7	11
Rope pieces	0	2
Rope nooses**	0	16
Other fishing equip.	1	1
Fishing Total	8 (53%)	30 (75%)
Fishing items per 100 nests	*3.04*	*10.3*
Other plastics	4	5
Packaging	3	5
Other (non-fishing) Total	7 (47%)	10 (25%)
Other items per 100 nests	*2.7*	*3.4*
All items	15	40
Items per 100 nest	*5.7*	*13.8*

* Snoods are pieces of line that attach the hooks to the main line
**Rope nooses are pieces of rope used to suspend toothfish in blast freezers (see Fig. 2.1).

During the 1998 whole-island census of incubating wandering albatrosses, a significantly higher density of marine debris was found next to nests on the north side of the island compared to the rest of the island ($\chi^2 = 9.1$; $P = 0.0025$) (Table 2.2).

Table 2.2 The frequency of occurrence of marine debris found next to wandering albatross nests on Marion Island, during the 1998 whole-island census of incubating birds.

Sector of the island	Nests searched	Debris per 100 nests
North	801	2.25
East	116	0.86
South	25	0
West	640	0.31
Total	1582	1.33

Entanglements

Four seabird entanglements were observed during the two years of this study, three of which involved toothfish longline fishing hooks and lines. All three of these incidents were observed during the 97/98 season. Prior to this report, only five reports existed of entanglements of seabirds at Marion Island since 1986 (Cooper and Huyser, 1995; D. Keith pers. comm.), of which only two involved fishing gear.

During the 96/97 season a macaroni penguin *Eudyptes chrysolophus* was observed with the ring from a plastic bottle top around its upper beak. During the 97/98 season a southern giant petrel was observed with a toothfish hook (with 7cm of monofilament nylon snood attached to it) through its leg, a sub-Antarctic skua *Catharacta antarctica* was observed with a monofilament nylon snood sticking out of its beak and a northern giant petrel *Macronectes halli* was found entangled with two toothfish hooks attached to each other by single piece of monofilament nylon. One hook was lodged in the oesophagus of the bird while the other was hooked in its wing.

Marine debris in carcasses

Ten seabird carcasses were found to contain anthropogenic items. Five of these (three lesser sheathbills *Chionis minor,* a southern giant petrel and a white-chinned petrel *Procellaria aequinoctialis*) contained small amounts of industrial pellets and other plastic pieces in the gizzard, while five (three wandering albatrosses, a southern giant petrel and a white-chinned petrel) contained large loads of marine debris (>100cm^3) situated in the proventriculus. All five of these incidents involved marine debris associated with the toothfish fishery. One wandering albatross chick and a white-chinned petrel chick were found dead with toothfish hooks in their stomachs. The hook found in the white-chinned petrel chick stomach had a

59 cm monofilament nylon snood attached to it, and had an estimated total volume of 150 cm^3. Three carcasses (two wandering albatross chicks and one southern giant petrel) contained "rope nooses". One wandering albatross chick carcass contained seven "rope nooses", which were entangled in squid beaks to make up a total volume of about 1000 cm^3.

DISCUSSION

Incidental finds

These data show a large increase in both the total amount of debris collected, as well as the proportion of debris originating from the fishing industry. As I collected *all* debris (i.e. there was no bias in the *type* of debris collected), I conclude that that the observed increase in proportion of fisheries derived items reflects an increased association of the large procellariiforms breeding on Marion Island with fishing vessels. All the hooks found in this study originated from toothfish longline operations, indicating that this interaction was almost certainly with the toothfish vessels operating around Marion Island. The reasons for the comparatively low number of tuna longline hooks found on Marion prior to this study are probably two-fold. Firstly, the tuna longline fishery is concentrated along the Sub-tropical Front and thus less accessible to breeding birds. Secondly, albatrosses and petrels obtain most toothfish hooks from toothfish heads which are removed during processing and dumped, without the hooks removed (Huin & Croxall 1996, M. Purves and R. Wanless pers. comm.). Only the fins of the tuna are removed during processing (Robertson 1998), thus precluding this route of acquiring hooks.

The highest proportion of fishing gear (relative to other debris) was found next to wandering albatross nests, followed by southern giant petrels and grey-headed albatrosses. This trend follows a decrease in body size, and can be explained by the fact that most of the fishing gear found on the island (i.e. hooks and "rope nooses") are attached to large items of offal when jettisoned from the vessels (e.g. hooks are embedded in toothfish heads or whole specimens of fish bycatch). While smaller seabird species are able to rip pieces of flesh from these large items of offal, only the larger birds are able to swallow them whole, thus ingesting the attached fishing gear. This has been verified by scientific observers aboard sanctioned toothfish longliners (J. Enticott, M. Purves, R. Wanless and B. Watkins pers. comm.). Large body size is also an advantage in the intense competition for offal, which exists around these vessels.

The 15 toothfish hooks found in association with wandering albatross nests at Marion Island during 1997/98 is less than the 27 hooks found associated with wandering albatrosses at Bird island, South Georgia, during 1993/94 (Huin & Croxall 1996). This is notwithstanding the fact that Marion Island has a larger breeding population (Gales 1998) and that the number of hooks set in the respective years were similar (4.7 million for Marion Island (Chapter 1) and 4.4 million for South Georgia (Huin & Croxall 1996)). However, the total fishing effort around Marion was almost certainly much higher, due to the presence of a substantial Illegal, Unregulated and Unreported (IUU) fishing fleet during 1996/97 (Chapter 1). As toothfish longlining in the close vicinity of South Georgia started a lot earlier than at Marion Island, a higher level of familiarity of South Georgia birds in scavenging offal from toothfish vessels could account for these observed differences. However, factors such as the diligence of observers in preventing hooks from being jettisoned will also have an effect.

Standardised checks of wandering albatross colonies

This study confirmed the increase in marine debris and fishing gear associated with seabirds, from the 96/97 to the 97/98 season. This increase was largely due to a three-fold increase in fishing gear, while the amount of "other" (non-fishing) debris remained relatively unchanged between the two seasons. This large increase is particularly interesting when we consider that the large influx of IUU fishing vessels took place during the latter half of 1996 and dropped off during the 1997/98 season (Purves 1997). However, diet sampling and tracking studies of wandering albatrosses at Marion Island (Chapter 3) showed that it was mainly during the early chick-rearing stage (May-July) that wandering albatrosses made short foraging trips and utilized offal from toothfish vessels. The major influx of IUU vessels close to the island only occurred during the latter part of 1996 (i.e. after the early chick-rearing period) and chicks from this season would thus have mostly avoided being fed large amounts fishing gear by their parents. However during 1997 IUU vessels were present throughout the season, allowing wandering albatross parents to rely heavily on offal as a supplementary source of food for their small chicks (Chapter 3). Consequently, a large increase in the number of hooks and fisheries debris was only noted during 1997.

Three records of two hooks (of different levels of degradation) at a single nest indicate that certain breeding adults may be using offal from fishing vessels as an easy source of food on a

repeated basis, thus exposing themselves to accumulative dangers of debris ingestion and incidental mortality.

The significantly higher density of nest debris on the north side of the island is interesting, as during 1996-98 most of the toothfish sets took place on the north and eastern side of the island (Chapter 1, Fig.1.1). This seems to indicate there may be some segregation in foraging zones utilized by breeding adults during short foraging trips. This will result in different longline related impacts at these sub-populations.

Entanglements and debris found in carcasses

More seabird entanglements and carcasses containing fishing gear were observed during the last eight months of this study, than over the past 11 years. The fact that some hooks were severely corroded by the digestive fluids indicates that birds could be absorbing harmful chemicals into their systems from these items. Ryan *et al.* (1988) showed a positive correlation between plastic loads by the stomachs of Great Shearwaters *Puffinus gravis* and polychlorinated biphenyls (PCBs) in the fat tissues, indicating that it is possible that harmful chemicals may be absorbed from marine debris in the digestive tract. These chemicals may lead to indirect effects on body condition, and thus survival probability. Large pollutant loads, as observed in some carcasses during this study, can also impair feeding activity (Ryan 1988), which will in turn lead to reduced body condition and possible mortality. Sievert & Sileo (1993) also showed that high plastic loads reduced the fledging mass of albatrosses. This would lead to decreased survival probabilities of these fledglings during their critical maiden flight.

These indirect impacts on both chicks and adults should be taken into account when the impact of longline fisheries on seabird populations is considered as a whole. Scientific observers aboard sanctioned fishing vessels should be meticulous about checking that marine debris (especially hooks in fish heads) are not thrown overboard (as required by South African and CCAMLR fishery regulations).

Appendix 1.1 Summary of all marine debris found next to seabird nests at Marion Island (both incidentally and by means standardised searches) from May 1996 to April 1998.

Type of pollutant	Species	96/97	97/98	Total
Hooks	Grey-headed albatross		1	1
	Southern giant petrel		3	3
	Sub-Antarctic skua	1		1
	Wandering albatross	3	15	18
		4	19	23
Snoods [1]	Grey-headed Albatross		3	3
	Southern giant petrel		1	1
	Wandering albatross	5	2	7
	White-chinned petrel		2	2
		5	8	13
Rope	Grey-headed albatross	1	8	9
	Macaroni penguin		1	1
	Southern giant petrel		3	3
	Wandering albatross		4	4
		1	16	17
Rope Nooses [2]	Southern giant petrel		11	11
	Sub-Antarctic skua		1	1
	Wandering albatross		48	48
		0	60	60
Other Fishing Gear	Grey-headed albatross		4	4
	Northern giant petrel		1	1
	Southern giant petrel	1	3	4
	Wandering albatross	1	2	3
		2	10	12
Fishing Gear Total		12 (22%)	113 (54%)	125
Pieces of Bottles	Grey-headed albatross	2	5	7
	Northern giant petrel		1	1
	Southern giant petrel	2	7	9
	Wandering albatross		1	1
		4	14	18
Other plastics	Grey-headed albatross	12	28	40
	Northern giant petrel	1	1	2
	Southern giant petrel	4	23	27
	Lesser sheathbill		1	1
	Sub-Antarctic skua	1	3	4
	Wandering albatross	7	6	13
	White-chinned petrel		1	1
		25	63	88
Packaging	Grey-headed albatross	1	7	8
	Northern giant petrel	3		3
	Salvin's prion		1	1
	Southern giant petrel	5	6	11
	Sub-Antarctic skua	1		1
	Wandering albatross	3	5	8
	White-chinned petrel		1	1
Packaging Total		13	20	33
Other (non-fishing) Total		42 (78%)	97 (46%)	139
Grand Total		54	210	264

[1] Snoods are the pieces of line that attach the hooks to the main line
[2] Rope Nooses are pieces of rope used to suspend Toothfish in blast freezers (see Fig 2.1).

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CHAPTER 3

Foraging interactions of wandering albatrosses *Diomedea exulans* breeding on Marion Island with longline fisheries in the southern Indian Ocean

ABSTRACT

Wandering albatrosses *Diomedea exulans* are frequently killed when they attempt to scavenge baited hooks deployed by long-line fishing vessels. The foraging ecology of wandering albatrosses breeding on Marion Island was studied in order to assess the scale of interactions with known long-line fishing fleets. During incubation and late chick-rearing, birds foraged farther away from the island, in warmer waters, and showed high spatial overlap with areas of intense tuna *Thunnus* spp. long-line fishing. During early chick-rearing, birds made shorter foraging trips and showed higher spatial overlap with the local Patagonian toothfish *Dissostichus eleginoides* long-line fishery. Tracks of birds returning with offal from the toothfish fishery showed a strong association with positions at which toothfish long-lines were set and most diet samples taken during this stage contained fisheries-related items. Independent of these seasonal differences, females foraged farther from the islands and in warmer waters than males. Consequently, female distribution overlapped more with tuna long-line fisheries, whereas males interacted more with the toothfish long-line fishery. These factors could lead to differences in the survival probabilities of males and females. Non-breeding birds foraged in warmer waters and showed the highest spatial overlap with tuna long-line fishing areas. The foraging distribution of Marion Island birds showed most spatial overlap with birds from the neighbouring Crozet Islands during the late chick-rearing and non-breeding periods. These areas of foraging overlap also coincided with areas of intense tuna long-line fishing south of Africa. As the population trends of wandering albatrosses at these two localities are very similar, it is possible that incidental mortality during the periods when these two populations show the highest spatial overlap could be driving these trends.

INTRODUCTION

Wandering albatrosses *Diomedea exulans* are one of the most renowned of all ship-following seabirds and are highly opportunistic scavengers (Croxall & Prince 1994). It is thus not surprising that significant numbers of these birds are killed when attempting to scavenge baited hooks deployed from long-line fishing vessels (e.g. Brothers 1991, Gales *et al.* 1998). Nor is it surprising that this species, with its small global population and extreme k-selected life history, has experienced population decreases at several breeding locations (Gales, 1998). Incidental mortality in long-line fishing operations has been identified as the main cause of population decreases at several localities (Croxall *et al.* 1998, de la Mare & Kerry 1994, Weimerskirch & Jouventin 1998).

Historically, long-line fishing effort in the Southern Ocean has varied both spatially and temporally (Polacheck & Tuck 1995). Pelagic long-line fishing for tuna *Thunnus* spp. started in the early 1960s. In the southern Indian Ocean, effort increased to a peak in the mid 1980s before decreasing during the late 1980s. The early 1990s once again saw a resurgence in effort that continued until the late 1990s (Tuck & Bulman 2001).

The late 1980s saw the development of another large long-line fishing industry in the Southern Ocean, demersal long-line fishing for Patagonian toothfish *Dissostichus eleginoides* (Brothers *et al.* 1999). This fishery is concentrated on the shelf areas surrounding the sub-Antarctic islands and at sea mounts. Fishing commenced in the austral summer of 1988/89 around South Georgia, South Atlantic Ocean (Dalziell & De Poorter 1993), and was followed by fishing around Kerguelen, southern Indian Ocean, (Cherel *et al.* 1996) in 1990. It was not until late 1996 that sanctioned (or legal) fishing started around the Prince Edward Islands after considerable poaching by Illegal, Unregulated and Unreported (IUU) vessels (Ryan *et al.* 1997).

It is also important to note several differences between these two major long-line fisheries. Firstly, wandering albatrosses are frequently killed in the pelagic tuna fishery (e.g. Gales *et al.* 1998, Ryan & Boix-Hinzen 1998) but are hardly ever killed in demersal toothfish long-line operations around Marion Island (Chapter 1), despite large numbers being in attendance during hauls (B.P. Watkins unpubl. data). This is presumably due to the faster-sinking demersal toothfish line only being accessible to the smaller, more

manoeuvreable albatrosses and petrels. Secondly, toothfish long-line operations produce large amounts of offal (particularly toothfish heads) and bycatch species (mostly grenadiers, Family Macrouridae) of a size accessible to wandering albatrosses, while tuna long-line fishing operations produce little offal (only the tail is removed) (Robertson 1998).

Consequently, according to their geographical position, different populations of wandering albatrosses are (and have previously been) exposed to varying degrees of risk of incidental mortality by long-line fishing as well as possible benefits derived from supplementary feeding on fishery discards. Furthermore, risks and benefits may vary within a population due to age, sex and seasonal differences in foraging movements/migration patterns. It thus necessary to understand the foraging ecology of each population in relation to the spatial distribution of local long-line fishing effort, in order to understand the complex effects on the population.

Marion Island is the single most important breeding island for wandering albatrosses in the world, hosting up to 1 900 breeding pairs annually (Chapter 6), and the Prince Edward Islands (consisting of Marion and the smaller neighbouring Prince Edward Island) are home to 36% of the annual global breeding population (Gales 1998). The foraging ecology of wandering albatrosses breeding at Marion Island was studied in order to understand the interactions with long-line fishing in the southern Indian Ocean. This chapter reports; 1) the foraging range and movements of wandering albatrosses breeding on Marion Island and the estimated level of interaction with known long-line fishing areas, and 2) sex and seasonal differences in the exposure to the risks and/or benefits of the various long-line fishing operations.

METHODS

This study was conducted on Marion Island (46°54'S, 37°45'E) between June 1996 and March 1998. Most observations were conducted in two study colonies containing individually marked birds of known sex and age, situated on the north east coast of the island. The study was conducted by means of: 1) direct observations of duration of foraging trips (i.e. intervals between a parent attending a nest), 2) tracking foraging trips

using Platform Terminal Transmitters (PTTs) and Geo-locating Sensors (GLSs), and 3) collecting diet samples.

Table 3.1 Details of the deployment of tracking devices on wandering albatrosses breeding on Marion Island.

Stage	Month	PTTs		GLSs		Total	
		Deploy-ments	Foraging Trips	Deploy-ments	Foraging Trips	Deploy-ments	Foraging Trips
Incubation	Jan/Feb	4	4	7	7	11	11
Early chick-rearing	May/Jun	8	27	6	7	14	34
Late chick rearing	Aug/Sep	10	26			10	26
	October			4	5	4	5
Desertions/very long foraging trips		3	3	1	1	4	4
Total		25	60	18	20	43	80

Studies were conducted at three separate periods during the breeding season: 1) incubation (January - mid-March), 2) early chick-rearing (May - June), and 3) late chick-rearing (September - October). Details of the number of devices deployed during each breeding stage are given in Table 3.1.

Four foraging trips of >40 days were considered to be more indicative of non-breeding foraging areas. Two birds did not return to the island for more than 60 days after deployment (and long after their PTTs had ceased to transmit locations). While the other two birds did return to the island after more than 40 days, the length of these foraging trips were more than three times longer than the next longest recorded foraging trip during the chick-rearing period. These foraging trips were thus considered to be abnormal and not indicative of foraging areas utilized by birds seeking to provide for their chicks. As the foraging areas utilized on these two trips were very similar to those utilized by the two birds that did not return to the colony, these four trips were considered separately from the rest of the breeding birds.

Duration of incubation shifts was measured by means of daily visits to the colony to record which mate was incubating. Twenty four nests were monitored for a period of 70 days. Duration of foraging trips during chick rearing was measured by means of observations at five-minute intervals from first light to last light, from a sheltered vantage-point within the colony. During the early chick-rearing period, 13 nests were observed continuously for 21 days, while during the late chick-rearing period 10 nests were observed continuously for 22 days

Breeding wandering albatrosses were tracked using either ST10 Platform Transmitter Terminals (PTTs) manufactured by Telonics (U.S.A.) (85g, 90mm×42mm×17mm) and packaged by Sirtrack Ltd. (New Zealand), or pillbox Geo-locating Sensors (GLSs) manufactured by Driesen and Kern (Germany) (65g, 90mm×15mm diameter). The PTTs transmitted at 90 second intervals and were monitored using the CLS-ARGOS satellite tracking system. This system uses the NOAA (National Oceanic and Atmospheric Administration, USA) satellites to receive signals from the PTTs. These data are then relayed to CNES (Centre National des Etudes Spatiales) where the location of the device is determined. The average interval between successful locations was about two hours. GLSs determine position by means measuring light intensity at 60 second intervals. This information is stored on a data logger and downloaded onto a computer once the device has been retrieved. These data were analysed using algorithms within the programme MULTITRACE (Jensen Software Systems, Germany). Briefly, since daylength is Julian day- and latitude-dependant and local noon is longitude dependant, the geographic position of the equipped animal can be determined. This procedure gives two positional fixes per 24 hours, which are nominally taken to be around mid-night and mid-day. The various procedures used to minimise errors in positional fixes are detailed in Welch & Eveson (1999), Wilson *et al.* (in press), and Wilson *et al.* (2002).

PTTs and GLSs weighed <100 g, and were attached to feathers on the back of the birds (approximately between the wings) by means of adhesive tape. Care was taken to ensure that the light sensor of the GLS was exposed when the bird's wings were folded. The attachment procedure usually took < 15 min. During the incubation stage, birds were captured immediately after they had been relieved of their incubation shift by their mate. No birds deserted and no eggs were broken due to handling, during this stage. During the chick-rearing stages, birds were captured soon after they had completed feeding their chick. Devices were left on for successive foraging trips. PTTs were left on for a minimum of 15 days, after which they were removed at the first opportunity. Two of the 43 birds (5%) that devices were deployed on, deserted their chicks and did not return to the colonies. Both these chicks still fledged, due to the efforts of the other mate. These desertions could have been due to the disturbance caused by the attachment procedure or the effect of the device itself. However, desertions do occur under natural conditions, when the body condition of an adult drops below a critical level (Weimerskirch 1998).

Movement data were plotted and analysed spatially using ARCVIEW GIS Version 3.0a (Environmental Systems Research Institute, U.S.A). Due to the large scale movements made by these birds and moderate level accuracy required for our analyses, all location classes of PTTs were considered unless the location proved to be implausible according to maximum flying speeds predicted by Pennycuik (1982). Distances were calculated using an equidistant azimuthal (south pole) projection. Bird movements were analysed in relation to monthly remote-sensed sea surface temperature data (at 1 degree resolution), available from Integrated Global Ocean Services System (IGOSS) on the world wide web (http//ingrid.ldgo.columbia.edu/SOURCES/.IGOSS/).

The spatial extent of the tuna long-line fishing effort in the southern Indian Ocean for the period of the study was calculated by Geoff Tuck from data reported to the Indian Ocean Tuna Commission (IOTC) and the International Commission for the Conservation of Atlantic Tunas (ICCAT). The latitude and longitude of all lines set by sanctioned Patagonian toothfish long-line fishing vessels within the South African EEZ were made available by the South African Department of Marine and Coastal Management. The boundary of the toothfish long-line fishing zone is defined as the 95% probability contour of a kernel home-range analysis (Worton 1989). For the analysis of GLS data a 50 km buffer was created around this boundary, to accommodate the predicted level of accuracy of these devices.

A total of 53 diet samples was collected during the period May 1996 to October 1997. Most (42) diet samples were taken from chicks that had been fed by adults carrying a tracking device. The rest of the samples were taken from randomly selected chicks. Samples were obtained by means of inverting the chick over a bucket and gently squeezing the stomach while massaging the throat. Samples were taken to the laboratory where they were weighed, analysed and all identifiable hard parts removed (i.e. squid beaks, otoliths and fish bones). The soft parts were then liquidized and fed back to the chick (within 12 h), by means of large syringe (volume *ca* 2.5 l), attached to a soft polypropylene tube (1.5 cm diameter) which was inserted down the oesophagus of the chick. This procedure allowed us to sample chicks of parents carrying tracking devices, more than once (maximum of three times) during a study period (*ca* 25 days). Chicks were not re-fed if they had been fed by their other parent during the period it took to

analyze the sample. Samples were taken during the first part of 1996 (prior to the start of toothfish longlining in the close vicinity of Marion Island) and throughout 1997 (during the first full year of sanctioned fishery). These samples were also compared to samples taken during 1988/89 by Cooper *et al.* (1992). A list of all bycatch species of the toothfish long-line fishery was obtained from observers aboard these vessels (B.P. Watkins pers. comm.). The approximate mass of toothfish and fish bycatch species found in stomach samples were calculated from the otolith lengths, using regression equations in Williams & McEldowney (1990).

Statistical analyses follow Zar (1984). Statistical significance was assumed at the $P < 0.05$ level, but due to the relatively small sample sizes characteristic of this type of work, all results with $P \leq 0.1$ are also reported. For all analyses involving foraging trip parameters (i.e. duration and range), the foraging trip was used as the statistical unit. This was deemed acceptable after a Kruskal Wallace (non-parametric) Analysis of Variance confirmed that variation between successive trips of a single individual was greater than the variation between individuals ($n = 24$, $H_c = 9.948$, $P > 0.99$). Individual birds (which were tracked for successive foraging trips) were considered as the statistical unit for all spatial analyses (i.e. proportions of time that individuals spent in sea surface temperature zones or within fishing zones). Data presented as percentages were arcsine transformed prior to performing statistical tests.

RESULTS

Foraging trip duration and range

The duration of foraging trips varied considerably throughout the breeding season. Mean foraging trip duration was the longest during the incubation period (7.5 ± 4.5 days) and shortest during the early chick-rearing period (2.7 ± 2.4 days). The mean foraging trip duration was slightly longer during the late chick-rearing period, but this was not significantly different. Male foraging trip duration was significantly shorter than females during both early and late chick-rearing (Table 3.2). This was due to the much higher proportion of male foraging trips that were < 1 day long ($\chi^2 = 21.3$, $P < 0.0001$) (Fig. 3.1). During late chick-rearing females also made more long foraging trips (> 8 days) than during early chick-rearing ($\chi^2 = 4.82$, $P = 0.028$) (Fig. 3.1).

Table 3.2 Average duration of foraging trips made by male and female wandering albatrosses breeding on Marion Island (n = number of foraging trips).

Chick-rearing Stage	Average length of foraging trip (days)			*U* Test	*P*
	Males ± SD (n)	Females ± SD (n)	Total ± SD (n)		
Early (June)	2.4 ± 2.3 (83)	3.1 ± 2.6 (50)	2.7 ± 2.4 (133)	1644	0.0453
Late (September)	2.4 ± 2.6 (58)	4.4 ± 3.4 (26)	2.98 ± 3.0 (84)	1410	0.0033

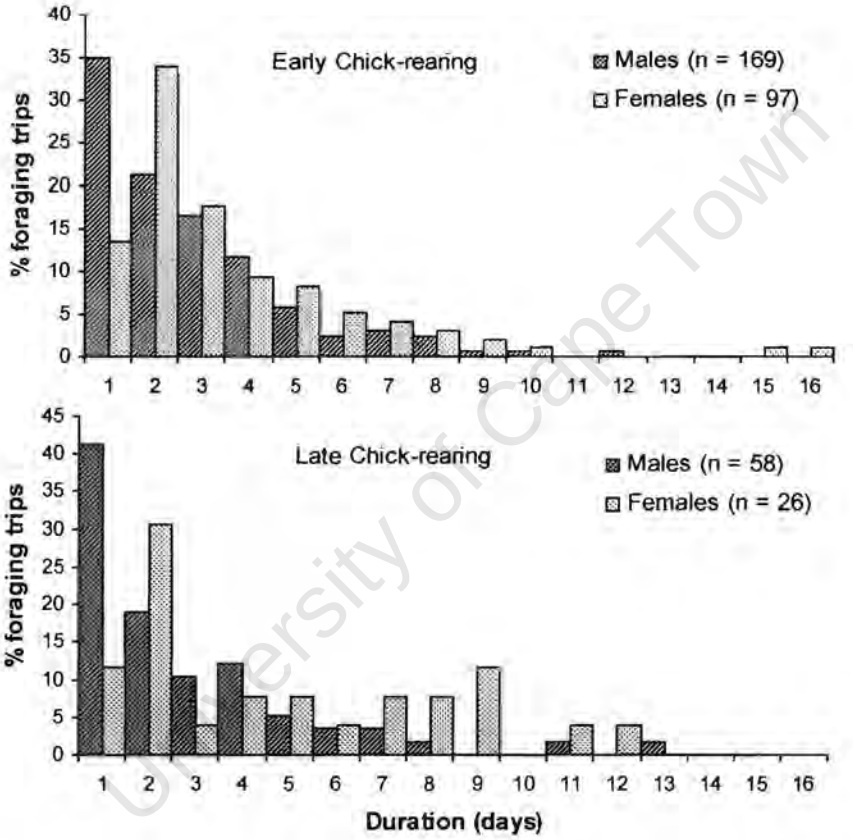

Figure 3.1 Frequency distribution of the duration of foraging trips during early chick- rearing (May/June) and late chick-rearing (September).

These results also supported the results of birds tracked by means of PTTs (Table 3.3). During the incubation period, tracked birds moved farthest from the island, while during chick-rearing the mean foraging range was reduced to almost half. Mean foraging range also varied within the chick-rearing period. During early chick-rearing, tracked birds displayed a more restricted foraging range than during late chick-rearing. Males also tended to have more restricted foraging ranges than females. Although none of these means were statistically different, this was probably due to the small sample sizes and the

bimodality of the data. The frequency distribution of male foraging ranges was distinctly bimodal, with peaks at <100km and at 500-600 km, while female foraging ranges only displayed a single peak at 400-500 km (Fig. 3.2).

Table 3.3 Mean maximum foraging range of breeding wandering albatrosses, tracked by PTTs from Marion Island (n = number of foraging trips).

Breeding Period	Mean Maximum Foraging Range (km)		
	Males ± SD (n)	Females ± SD (n)	Total ± SD (n)
Incubation	456 ± 1 (2)	1402 ± 1292 (2)	929 ± 924 (4)
Chick-rearing	426 ± 305 (29)	608 ± 497 (24)	508 ± 409 (53)
Early (June)	355 ± 214 (15)	444 ± 236 (12)	394 ± 225 (27)
Late (September)	502 ± 372 (14)	773 ± 634 (12)	627 ± 518 (26)
Breeding Total	428 ± 295 (31)	669 ± 584 (26)	538 ± 462 (57)

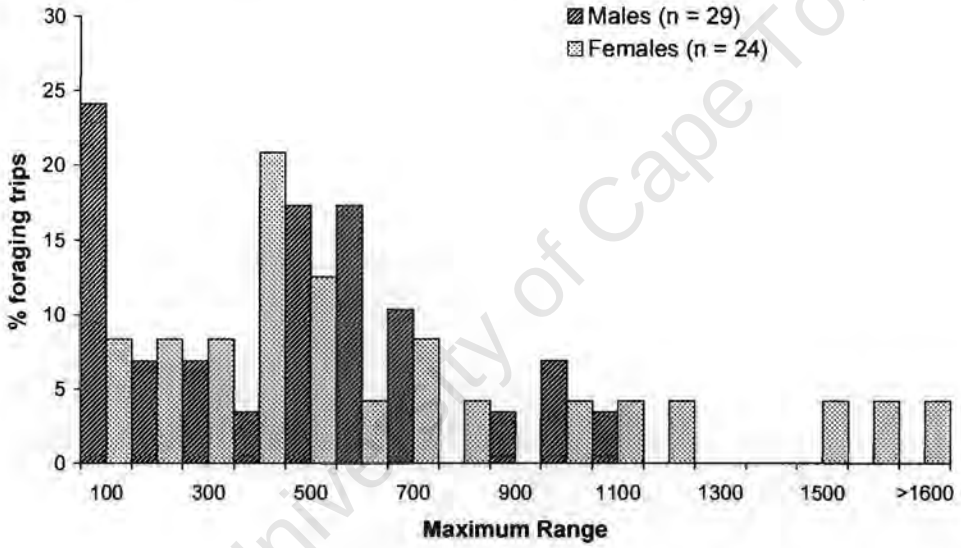

Figure 3.2 Frequency distribution of maximum foraging ranges of Wandering Albatrosses breeding on Marion Island, tracked by means of PTTs during the chick-rearing period.

Habitat utilisation

Differences in foraging trip duration and range throughout the breeding season resulted in spatial differences in habitat utilization (Fig. 3.3). During the early chick-rearing period birds spent significantly less time in waters warmer than 12°C (i.e. the Sub-tropical Frontal Zone and waters to the north of this) than during the rest of the breeding season ($U = 98.5$, $P = 0.0249$) (Table 3.4). Non-breeding birds moved rapidly away from

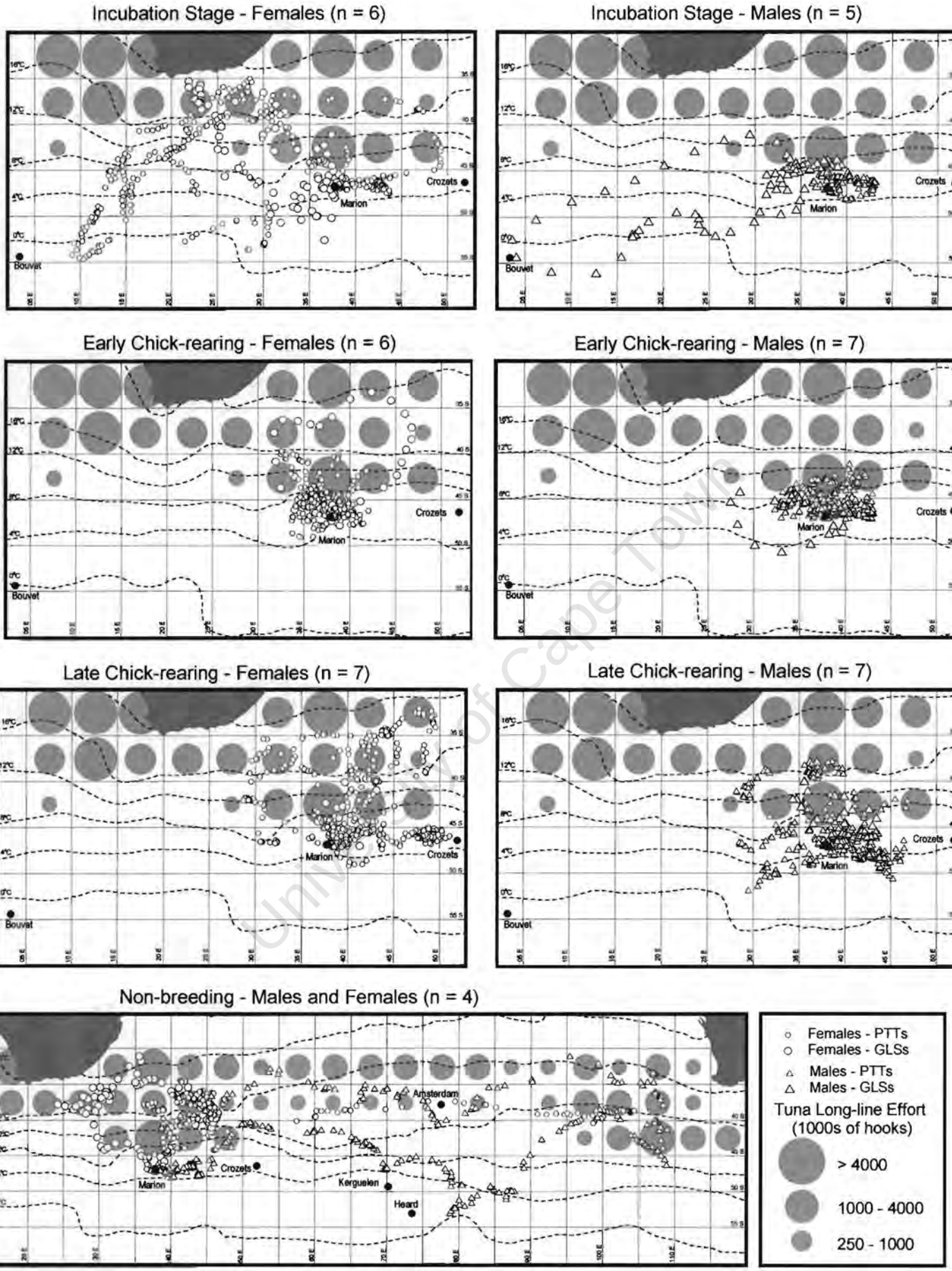

Figure 3.3 Foraging distribution of Wandering Albatrosses tracked from Marion Island in relation to Tuna long-line fishing effort (n = number of individuals tracked).

Table 3.4 The average proportion of time spent in waters warmer than 12°C by wandering albatrosses breeding on Marion Island (n = number of individuals).

Stage	% Time in waters warmer than 12°C			Males vs Females	
	Males ± SD (n)	Females ± SD (n)	Total ± SD (n)	*U* Test	*P*
Incubation	10.4 ± 12.0 (5)	39.1 ± 32.0 (6)	24.8 ± 27.4 (11)	8	0.246
Chick-rearing	7.7 ± 14.0 (15)	22.3 ± 29.0 (13)	14.5 ± 23.0 (28)	66	0.147
Early (June)	0.1 ± 0.2 (8)	15.2 ± 26.7 (6)	6.5 ± 18.2 (14)	13.5	0.181
Late (September)	16.4 ± 17.1 (7)	28.3 ± 31.6 (7)	22.4 ± 25.2 (14)	19	0.535
Breeding Total	8.4 ± 13.3 (20)	27.0 ± 29.9 (19)	17.2 ± 24.3 (39)	125	0.067
Non-breeding			58.8 ± 26.5 (4)		

Table 3.5 The average proportion of time spent within the main tuna longline fishing areas by wandering albatrosses breeding on Marion Island. The main tuna longline fishing areas are represented by 5° grid squares which supported >1 million hooks for the year of the study. *n* = number of individuals

Stage	% Time within tuna longline fishing areas			Males vs Females	
	Males ± SD (n)	Females ± SD (n)	Total ± SD (n)	*U* Test	*P*
Incubation	24 ± 18 (5)	32 ± 25 (6)	28 ± 22 (11)	11	0.54
Chick-rearing	25 ± 21 (15)	43 ± 17 (13)	34 ± 20 (28)	48	0.024
Early (June)	24 ± 18 (8)	37 ± 15 (6)	29 ± 17 (14)	14	0.23
Late (September)	27 ± 26 (7)	49 ± 17 (7)	38 ± 24 (14)	12	0.13
Breeding Total	25 ± 20 (20)	40 ± 20 (19)	32 ± 21 (39)	108	0.023
Non-breeding			48 ± 13 (4)		

the island and spent most of their time in waters warmer than 12°C. During the breeding season females spent more time in waters warmer than 12°C than did males (Table 3.4).

These changes in the spatial utilization of their habitat throughout the breeding season also resulted in differences in spatial overlap with the main long-line fishing grounds (Fig. 3.3). Females spent significantly more time in areas of moderate to high tuna longline fishing effort (>1 million hooks for the year) than did males, throughout the breeding season. This difference was most significant for the chick-rearing period (Table 3.5). Utilization of tuna longline fishing areas was highest during the late chick-rearing period when females spent almost half their time in these areas (Table 3.5). Male utilization of

tuna fishing areas did not vary much during the breeding season. Non-breeding birds also spent almost half their time in areas of moderate tuna fishing effort (Table 3.5).

Conversely, due to their more restricted foraging range during the early chick-rearing period, birds spent more time within the boundaries of the local toothfish industry during this stage than during the rest of the breeding season (Table 3.6). Males spent more time within toothfish long-line fishing areas than females. This difference was greatest during the early chick-rearing period when males almost doubled their utilisation of this area compared to the rest of the breeding season (Table 3.6). Female utilization of toothfish longline fishing areas did not vary much during the season. Non-breeding birds moved rapidly away from the islands, spending hardly any time within the boundaries of the toothfish long-line fishery.

Table 3.6 The average proportion of time spent within the Prince Edward Island toothfish fishing zone by wandering albatrosses breeding on Marion Island. The Prince Edward Island toothfish fishing zone is represented by the 95% probability contour of a kernal home range analysis (Worton 1989) of all toothfish longline sets made by sanctioned vessels during 1996-1998. *n* = number of individuals.

	% Time within toothfish fishing zone			Males vs females	
Stage	Males ± SD (n)	Females ± SD (n)	Total ± SD (n)	*U* Test	*P*
Incubation	20.1 ± 19.3 (5)	22.4 ± 22.7 (6)	21.4 ± 20.2 (11)	14.5	0.931
Chick-rearing	34.2 ± 24.1 (15)	19.7 ± 12.8 (13)	24.4 ± 20.7 (28)	60	0.088
Early (June)	42.7 ± 25.1 (8)	22.8 ± 13.2 (6)	34.2 ± 22.6 (14)	11	0.108
Late (September)	24.4 ± 20.4 (7)	17.0 ± 12.8 (7)	20.7 ± 16.8 (14)	19	0.535
Breeding Total	30.7 ± 23.4 (20)	20.5 ± 15.9 (19)	25.7 ± 20.5 (39)	145	0.211
Non-breeding			5.6 ± 6.2 (4)		

Diet analyses

The occurrence of fisheries-derived items in diet samples increased significantly after the start of the local toothfish long-line fishery in the close vicinity of Marion Island (Table 3.7). During 1997, almost 60% of samples contained fisheries-related items. This was largely due to a significant increase in known bycatch species of this fishery (mostly macrouriids) as well as toothfish heads. Fisheries-related litter (i.e. toothfish hooks, snoods and pieces of rope) also increased significantly (occurring in 25% of the 1997 samples) whilst the occurrence of other anthropogenic litter (i.e. of unknown origin)

remained constant over time. The most frequently occurring fisheries-derived litter were toothfish hooks (17% of samples), followed by "rope nooses" used to hang toothfish in blast freezers of certain long-line vessels (see Chapter 2) (8% of samples). One post-toothfish long-line fishing sample contained 10 such "rope nooses", weighing 101 g and with a volume of *ca* 500 cm^3.

Table 3.7 The frequency of occurrence of fishery-derived items in the diets of wandering albatrosses breeding on Marion Island before and after the start of the toothfish longline fishery around Marion Island. Data for 1988/89 are taken from Cooper *et al.* (1992).

Diet item	Frequency of occurrence (% of samples)			χ^2_1 Pre- vs Post-toothish longlining *P*
	Pre-toothfish longlining		Post-toothfish longlining	
	1988/89 (n=50)	Early 1996 (n=19)	1997 (n=36)	
Known toothfish bycatch species [1]	6	5	31	<0.005
Dissostichus eleginoides	0	0	8	<0.10
Fisheries offal total	6	5	39	<0.001
Fisheries related litter	0	0	25	<0.001
Other anthropogenic litter	10	5	3	ns
Anthropogenic litter total	10	5	28	<0.025
Samples containing any fisheries-derived items (ie. Offal or Fisheries Litter)	6	5	58	< 0.001

[1] *Cynomacrurus piriei* and *Macrourus holotrachys*.

The average mass of toothfish in the 1997 samples (as calculated from otolith dimensions) was 2.6 kg (n = 3; range = 2.1 –5.4 kg), whilst the average mass of the entire solid portion of the diet samples taken from these birds was only 577 g (range = 253 g – 875 g). This indicates that these toothfish were probably not ingested whole. Toothfish of this size are small compared to most taken commercially, but heads of larger fish are probably too large to swallow whole. The average mass of macrouriids was 847 g (n =4; range = 486 g – 1.1 kg), suggesting that these specimens may have been ingested whole. One sample containing a fresh toothfish head also contained fresh onion and apple skins, whilst another sample contained a toothfish otolith along with a rope noose and toothfish snood (line used to attach the hook to the mainline). One sample containing a macrouriid also contained a rope noose.

Seasonal differences in the consumption of fisheries-related litter supported our observations of seasonal changes in foraging distribution and range. Samples taken during

the early chick-rearing period contained significantly more toothfish long-line fishery offal products (i.e. toothfish heads and discards) than did those taken during the late chick-rearing period (Table 3.8). More than three-quarters of samples taken during the early chick-rearing period contained fisheries-related items. The occurrence of fisheries-related litter did not differ between these two periods.

Table 3.8 Seasonal changes in the frequency of occurrence of fishery-derived items in the diets of wandering albatrosses at Marion Island, 1997. Early chick-rearing = May/June; Late chick-rearing = September/October.

	Frequency of occurrence (% of samples)		χ^2_1 Early vs Late chick-rearing *P*
	Early chick-rearing (n=17)	Late chick-rearing (n=19)	
Fisheries offal[1]	59	21	<0.05
Fisheries related litter	24	26	ns
Other anthropogenic litter	6	0	ns
Anthropogenic litter total	29	26	ns
Samples containing any fisheries-derived items (ie. offal or fisheries litter)	76	42	<0.10

[1] This category includes: *Dissostichus eleginoides*, *Cynomacrurus piriei* and *Macrourus holotrachys*.

Four samples taken from chicks of PTT tracked parents contained very fresh items of offal. One parent returned with two Patagonian toothfish heads and three others returned with macrouriids. The tracks of these birds were confined mostly within the local toothfish long-line fishing area (Fig. 3.4). Three tracks (Fig. 3.4 a, b and c) passed close to the positions of long-lines that were set by sanctioned vessels during the actual foraging trip. No sanctioned vessels were in the area at the time that the fourth bird (Fig. 3.4d) captured a macrouriid, but this bird showed distinctive foraging behaviour within an area that was used extensively by IUU vessels (B.P. Watkins pers. comm.). It is thus probable that this bird was scavenging around an IUU fishing vessel.

DISCUSSION

Seasonal differences

Our results show several important seasonal differences in the foraging strategy of wandering albatrosses breeding at Marion Island. In summary, birds foraged closest to the

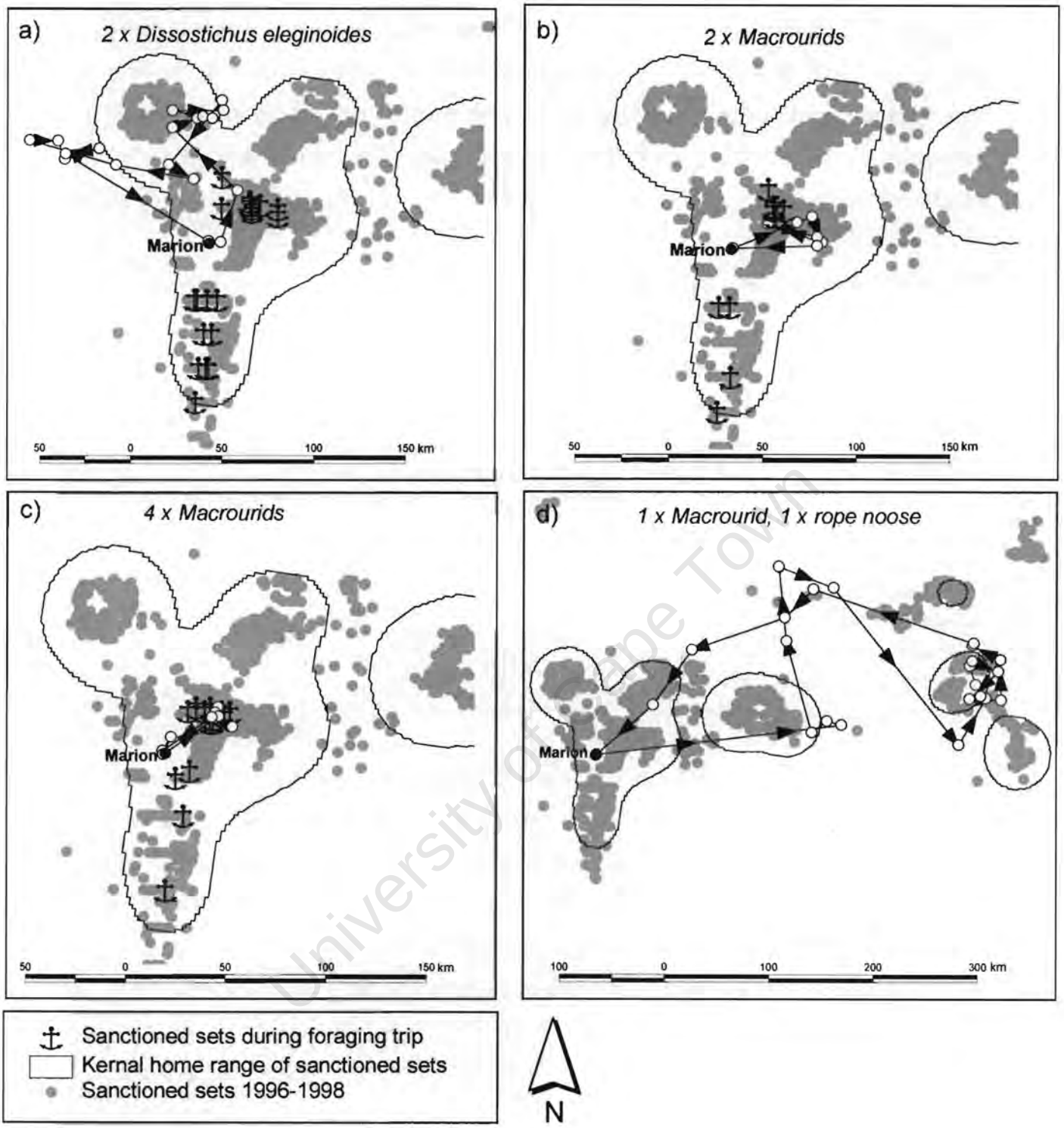

Figure 3.4 The foraging tracks of breeding wandering albatross adults that returned with fresh offal probably from toothfish long-liners.

island during the early chick-rearing period and foraged farther away in the warmer waters to the north of the island during both incubation and the late chick-rearing stage. These seasonal changes in foraging range are similar to those recorded for wandering albatrosses breeding at other localities (Weimerskirch *et al.*1993, Prince *et al.* 1998) and probably result from a compromise between the parent meeting its own energy requirements and those of its chick (Weimerskirch 1998).

These changes in foraging range result in seasonal changes in the spatial overlap and interaction with spatially disjunct long-line fisheries in the southern Indian Ocean. During the early chick-rearing period, when parents made more short foraging trips, a greater spatial overlap with the local Patagonian toothfish long-line fishing area as well as an increased reliance on offal produced by these vessels was noted . Although the frequency of occurrence of offal products was far higher during early chick-rearing, the occurrence of fisheries-related debris (i.e. hooks and ropes) did not differ from the late chick-rearing period. This is due to the fact that these items persist in the stomachs of the chicks long after they are ingested. The average mass (calculated from otolith lengths) of the toothfish ingested indicate that they were probably not ingested whole but rather as heads only. Toothfish heads initially were discarded during processing aboard most toothfish long-liners. Toothfish hooks are also probably ingested when heads are discarded without the hook being removed. The macrouriids (a discard species of the toothfish fishery), on the other hand, were of a size that could easily be consumed whole by these birds.

Despite this apparent increase in the availability of offal close to the island, no significant increase in breeding success was recorded (Chapter 7). However, the benefits of supplementary feeding of offal to chicks may have been offset by the large amounts of fisheries-related litter ingested (Chapter 2). A large increase in the amount of fishing gear in stomach samples was found co-incident with the start of the toothfish fishery. These results supported the large increase in the amount of fishing gear found around wandering albatross nests at Marion Island (Chapter 2). In some cases extremely high litter loads (>500 cm^3) were found in in wandering albatross chicks in this study as well (Chapter 2). Such high litter loads can lead to decreased appetite (Ryan 1988) and body condition (Ryan 1987). An increase in chick fatalities associated with the ingestion of fishing gear was also recorded (Chapter 2).

Despite this availability of large amounts of offal in the close vicinity of the island, birds foraged farther away from the island during the incubation, late chick-rearing and especially during the non-breeding periods. Foraging trips during these stages showed a preference for waters warmer than 12°C (i.e. the Sub-tropical Frontal Zone and waters to the north of this). In other words, birds only utilized offal produced by toothfish vessels when under the constraint of needing to feed a small chick at frequent intervals (i.e. therefore needing to locate food close to the island). When freed from this constraint (as in the extreme case of non-breeding birds), birds preferred to forage farther away from the island in the productive waters of the Sub-tropical Frontal Zone. The reasons for this may be complex, but intense competition in the close vicinity of the island (and specifically around fishing vessels) may be an important reason for these birds moving away from the island when allowed this freedom. Observers aboard toothfish long-liners fishing around Marion Island have reported up to 500 wandering albatrosses gathered around a single vessel during hauling (J.W. Enticott & B.P. Watkins unpubl. data).

This preference for foraging in warmer waters during the incubation, late chick-rearing and non-breeding periods, led to a higher spatial overlap with tuna long-line fisheries during these stages. Long-line fishing effort in the southern Indian Ocean is consistently concentrated during the 2nd and 3rd quarters of the year (i.e. April to September). On average 47% of the effort occurs from April to June (corresponding to the early chick-rearing period of wandering albatrosses) and 33% between July and September (overlapping with the late chick-rearing period). Only 12% of effort occurs between January and March (corresponding to the incubation period). It thus follows that the interaction between breeding wandering albatrosses and tuna longliners would be highest during the late chick-rearing period when utilization of fishing areas was high by both albatrosses and fishing vessels. However, as Wandering albatrosses are biennial breeders, there will be a large proportion of adult birds that are not breeding throughout the year. These non-breeding birds would thus be able to interact with tuna longliners during the period when most hooks are set (April to June). This study showed that birds released from the constraint of feeding a chick spent most of their time in the tuna fishing areas and will thus be exposed to a high risk of incidental mortality.

Differences between males and females

During the chick-rearing period, females consistently made longer foraging trips, foraging farther from the island and in warmer waters. This is probably the result of sexual dimorphism (Shaffer *et al.* 2001) and sexual segregation in foraging strategies (Weimerskirch *et al.* 1997a). They consequently spent more time in areas of intensive tuna long-line fishing, south of Africa. This was most pronounced during the late chick-rearing stage, when females increased their proportion of longer foraging trips. It is thus expected that during the breeding season females will experience a higher risk of incidental mortality from the tuna long-line industry, and that this risk would be highest during the late chick-rearing stage. No data on the sex composition of wandering albatrosses killed in the tuna fishery south of Africa are available. However data from long term monitoring colonies on Marion Island indicate that adult female survival was lower than that of males (Chapter 7). This was similar to data recorded from the Crozets and South Georgia (Croxall *et al.* 1990, Weimerskirch *et al.* 1997a), where a sex bias in incidental mortality by tuna longline fishing was implicated as the main reason. Wandering albatrosses are highly monogamous, and sex-biased mortality will not only decrease the number of potential breeding pairs, but will also decrease the fecundity of the population. Jouventin *et al.* (1999) showed that remating exerts an average reproductive cost of 15% of lifetime reproductive success.

Males consistently foraged closer to the island than females and spent more time in areas of toothfish long-line fishing. This was most pronounced during the early chick-rearing stage, when males doubled their utilization of this area. Males would thus benefit more from offal produced by these vessels. Although these short foraging trips are primarily aimed at meeting the energetic demands of the chick (Weimerskirch 1998) it is expected that large amounts of easily acquired offal will reduce the energetic costs incurred by the adult and thus improve its survival probability. Increased male survival will serve to further exacerbate a male bias in the population, which may have been created by a higher incidental mortality of females in the tuna long-line industry. Although the limited survival data since the start of the toothfish fishery are not statistically robust enough to detect differences between male and female survival, an increase in overall adult survival rates was detected since the beginning of the toothfish fishery (Chapter 7).

Foraging distribution in relation to other Indian Ocean populations

The foraging distributions of wandering albatrosses on Marion Island and neighbouring Iles Crozet Islands (*ca* 1000 km apart) showed varying degrees of spatial overlap during the breeding season (Fig. 3.5). During early chick-rearing, the foraging ranges of these two populations were almost totally non-overlapping. During late chick-rearing, the spatial overlap of foraging ranges was substantially greater, and occurred mostly in warmer waters to the north of Marion and south east of the African continent. This is an area of intense tuna long-line fishing and also the area used more frequently by females from both populations. Although only a small number of non-breeders from both populations have been tracked, available data suggest that during this stage birds from both populations disperse widely and show the greatest degree of overlap (this study; Weimerskirch & Wilson 2000). Once again, females showed the greatest affinity for the warmer waters north of the islands.

Wandering albatross populations at Marion and the Crozets show very similar population trends (Chapter 6) and annual adult survival rates were correlated (Chapter 7). Weimerskirch *et al.* (1997b) and Tuck *et al.* (2001) have attributed population trends at the Crozets to changes in adult survival caused by historical changes in tuna long-line fishing effort in the southern Indian Ocean. The similarities in trends of these two populations therefore suggest that either 1) exposure to the risk of incidental mortality is similar across the geographical ranges of both populations, or 2) incidental mortality occurring during the stages when these two populations show the greatest degree of spatial overlap with each other and known tuna long-line fishing areas is driving the similar population trends. From Fig. 3.3 it can be seen that the reason is unlikely to be the former, as tuna long-line fishing effort to the north and north east of the Crozets is far lower than to the north of Marion Island. It therefore seems likely that incidental mortality during the late chick-rearing and non-breeding stages is driving these populations trends, when the birds from these two populations show the greatest degree of spatial overlap with each other and the tuna long-line fishing areas south east of Africa (Fig. 3.3, Fig. 3.5). More specifically, as adult females from both populations have lower survival rates than males (Weimerskirch *et al.* 1997b, Chapter 7), forage farther north, in warmer waters, and show the greatest degree of spatial overlap with tuna longline fishing areas, it is likely that incidental mortality to adult breeding females during late chick-rearing and non-breeding stages is an important factor driving these population trends.

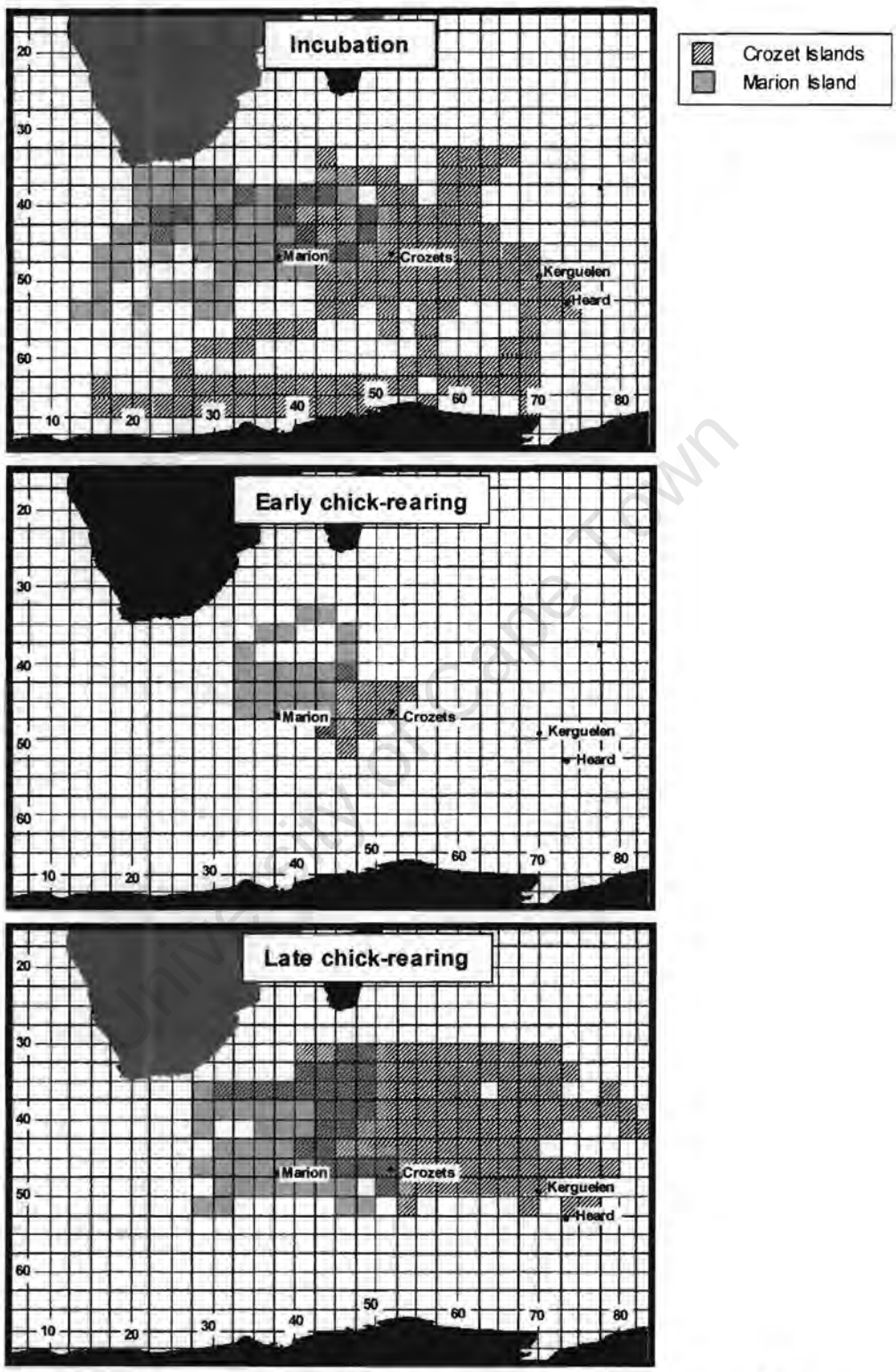

Figure 3.5 Foraging distribution of breeding wandering albatrosses tracked from Marion Island and the neighbouring Crozet Islands (fromWeimerskirch *et al.* 1993).

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CHAPTER 4

Foraging ecology of grey-headed albatrosses *Thalassarche chrysostoma* at Marion Island, southern Indian Ocean, in relation to longline fishing activity

ABSTRACT

Incidental mortality due to longline fishing has been implicated as the main cause for the global population decline in grey-headed albatrosses *Thalassarche chrysostoma*. Two of these fisheries, within the potential foraging range of grey-headed albatrosses breeding on Marion Island, have increased drastically over the past 5-10 years. In order to understand the impacts of these fisheries on the grey-headed albatross population breeding on Marion Island, we studied their foraging ecology by tracking their foraging trips and sampling their diets. During the incubation stage, birds made long foraging trips, mostly towards the Sub-tropical Front and Sub-Antarctic zones, bringing them into contact with areas of intense pelagic longlining for tuna *Thunnus* spp. Females spent a higher proportion of their time within these areas than males, and thus face a higher risk of incidental mortality from this fishery. During the early chick-rearing stage, foraging trips were shorter and to the southwest of the island in the Polar Frontal and Antarctic Zones, thus avoiding any contact with the tuna fishing areas. However, short foraging trips (<2 days) were made within the boundary of Patagonian toothfish *Dissostichus eleginoides* longline sets around Marion Island. Males made a higher proportion of short foraging trips and spent more time within the boundaries of the toothfish fishery than females. These differences may account for the male-biased mortality of grey-headed albatrosses observed in the toothfish fishery around Marion Island. Although a decrease in the annual breeding population has not been detected on Marion Island as yet, methods used to detect these changes are inaccurate in measuring short term population changes (<10 years) and the impacts of these fisheries may already have altered the demographic structure of this population.

INTRODUCTION

The Prince Edward Islands group (southern Indian Ocean), comprised of Marion and the smaller Prince Edward Island, is one of only seven breeding localities for the grey-headed albatross *Thalassarche chrysostoma* and collectively support *c.*10% (*c.* 9 000 pairs) of the global annual breeding population (Gales 1998, Chapter 6). Although the population on Marion Island appears to be stable and recently increasing, populations on South Georgia (representing 56% of world population) and Campbell Island have shown long term decreases in numbers, leading to this species being listed as vulnerable (Croxall & Gales 1998). Incidental mortality due to birds being drowned when they attempt to snatch baited hooks deployed by longline fishing vessels, has been implicated as a main cause for the global decline (Gales 1998).

Initial concern was focused on the pelagic tuna *Thunnus* spp. longline fishery (e.g. Brothers 1991, Murray *et al.* 1993). More recently, however, the development of demersal longline fisheries for Patagonian toothfish *Dissostichus eleginoides* on the shelf areas surrounding the main breeding localities of the sub-Antarctic avifauna has raised cause for concern (e.g. Ashford *et al.* 1995, Croxall & Prince 1996, Cherel *et al.* 1996). After intitially being overlooked as a possible fishing ground, sanctioned longline fishing for Patagonian toothfish within the 200 nautical mile Exclusive Economic Zone (EEZ) surrounding the Prince Edward Islands commenced in October 1996. This was after considerable 'poaching' by Illegal, Unregulated and Unreported (IUU) fishing vessels during the early part of 1996 (Purves 1997). During the first year of sanctioned fishing large numbers of seabirds were killed (Chapter 1). This included at least 126 grey-headed albatrosses killed by licensed vessels, but as large scale unsanctioned fishing continued throughout this period, it was estimated that more than 1000 grey-headed albatrosses could have been killed during the first four years of this fishery (Chapter 1). Examination of carcasses collected by scientific observers aboard sanctioned vessels revealed a strong male bias in all affected species; 86% of the grey-headed albatross carcasses were adult males (Chapter 1).

Grey-headed albatrosses are also killed in substantial numbers by pelagic tuna longline fisheries south of Africa (Ryan & Boix-Hinzen 1998) and off western Australia (Gales *et al.* 1998). Tuna longline fishing in the southern Indian Ocean is

largely concentrated around the Sub-tropical Front (Ryan & Boix-Hinzen 1998). This fishery reached its peak in the southern Indian Ocean during the mid 1980s and decreased to less than half during the early 1990s. During the mid 1990s, this fishery increased to *ca.* 80% of the 1985 peak. This effort once again tailed off during the latter part of the 1990s (Tuck & Bulman 2001).

Albatrosses exhibit an extreme k-selected breeding strategy. They display a low reproductive rate, high adult survival, delayed onset of breeding (up to 10 years). They also display strong mate fidelity (Warham 1996). Increased mortality due to longline fishing will thus have a complex effect on the demographics of a population that may not be immediately noticeable as a change in the number of birds attempting to breed annually (e.g. Weimerskirch *et al.* 1997a; Jouventin *et al.* 1999). Studies on wandering albatrosses *Diomedea exulans* have shown that decreasing adult survival is accompanied by a decrease in the age at first breeding (Croxall *et al.* 1990, Weimerskirch *et al.* 1997a), which could initially mask the signal. Also, seabird population trends are generally measured by the number of pairs attempting to breed each year. This measure is notoriously inadequate for measuring short term changes in population size (i.e. <10 years) of biennial breeding albatross populations (Gales 1997, Moloney *et al.*, 1994). However, as albatrosses have such low productivity and recruitment rates, population growth rate will take a very long time to stabilize after a perturbation (30-50 years in wandering albatrosses) (Moloney *et al.* 1994). As albatrosses display high site fidelity and breeding sites are limited and often distant from each other, longline fishing effort within the potential foraging ranges of these breeding populations and its resultant impacts may also vary markedly between populations. It is with this in mind that international conservation initiatives strongly urged research into the foraging ranges and ecology of affected albatross populations (e.g. Alexander *et al.* 1997, Gales 1993). The main objective of these initiatives is to determine the degree of spatial and temporal overlap of the foraging ranges of albatross populations with known longline fishing grounds and therefore the degree of exposure of these populations to the risk of incidental mortality.

Despite obvious threats from longline fishing operations within the potential foraging range of grey-headed albatrosses breeding at Marion Island, very little is known about their foraging ecology during the breeding season and their potential interaction with

these fisheries. Current knowledge is restricted to a study of the diet of grey-headed albatrosses at the Prince Edward Islands during the chick rearing period (Hunter & Klages 1989) and observations at sea (Abrams 1985). These studies suggest that most foraging activity is concentrated at the Sub-Antarctic front and the Polar Frontal Zone. In this study I: 1) present additional information on the foraging ecology of this population, 2) establish the level of spatial overlap with known fishing grounds while breeding, and 3) ascertain if there are any differences in the foraging behaviour of males and females, that may account for the high male-biased mortality in the local toothfish longline industry.

METHODS

A maximum of *ca* 7700 grey-headed albatross pairs breed annually in dense colonies on the southern coast of Marion Island (46°54'S, 37°45'E). Adults return to the colonies early in September, and eggs are laid during the middle of October. During the 1997/98 season, the first chicks hatched between 14 and 21 December 1997 and the first chicks fledged during the last week of April 1998. Adults weigh between 3.0 and 3.7 kg, with males being slightly heavier (Marchant & Higgins 1990).

I investigated the foraging ecology of breeding grey-headed albatrosses at Marion Island by means of tracking the foraging movements of breeding adults and diet sampling of chicks.

Foraging movements

Breeding grey-headed albatrosses were tracked for a total 117 days using two types of tracking devices: 1) ST10 Platform Transmitter Terminals (PTTs) manufactured by Telonics (U.S.A.) and packaged by Sirtrack Limited (New Zealand) (85g, 90mm×42mm×17mm), and 2) pillbox Geo-Locating Sensors (GLSs) manufactured by Driesen & Kern (Germany) (65g, 90mm×15mm diameter).

The PTTs transmitted at 90 second intervals and were monitored using the CLS-ARGOS satellite tracking system. This system uses the NOAA (National Oceanic and Atmospheric Administration, USA) satellites to receive signals from the PTTs. These

data are then relayed to CNES (Centre National des Etudes Spatiales) were the location of the device is determined. The average interval between successful locations was about two hours. GLSs determine position by means measuring light intensity at 60 second intervals. This information is stored on a data logger and downloaded onto a computer once the device has been retrieved. These data were analysed using algorithms within the programme MULTITRACE (Jensen Software Systems, Germany). Briefly, since daylength is Julian day- and latitude-dependant and local noon is longitude dependant, the geographic position of the equipped animal can be determined. This procedure gives two positional fixes per 24 hours, which are nominally taken to be around mid-night and mid-day. The various procedures used to minimise errors in positional fixes are detailed in Welch & Eveson (1999) and Wilson *et al.*(in press). As GLSs only acquire two positional fixes per day (i.e. at 12hr intervals) and thus cannot resolve the convoluted paths often followed by albatrosses, these data were ignored in any calculations requiring knowledge of total distance covered, or fine scale movements (i.e. <12 hr interval) such as time spent in the toothfish fishing zone (which was typically <12 hr per visit, for PTT-tracked birds).

The PTTs and GLSs were attached to feathers on the back of the birds (approximately between the wings) by means of adhesive tape. Care was taken to ensure that the light sensor of the GLSs was exposed when the bird's wings were folded. Devices were deployed on adults of known sex from a demographic study colony. Sex was determined by means of bill measurements (Ryan 1999). Birds with a depth of the bill at the nail (unguis) larger than 29 mm were deemed to be males, however both mates were measured and culmen length and minimum depth were also considered if the separation was not clear on depth at nail alone.

During late incubation (24 November to 17 December 1997) two males and two females were tracked for a total of 56 days using PTTs. Birds were captured immediately after they had been relieved of their incubation shift by their mates, and were taken to the side of the colony where the devices were attached. Attachment took 10-15 minutes. During early chick-rearing stage (20 January to 5 February 1998) three males and three females were tracked for a total of 61 days and 15 complete foraging trips, using two PTTs (on one male and one female) and four GLSs (on two males and

two females). Devices where attached to adults immediately after they had completed feeding their chick and were left on for successive foraging trips.

Movement data were plotted and analysed spatially using ARCVIEW GIS Version 3.0a (Environmental Systems Research Institute, U.S.A). Due to the large scale movements made by these birds and the low level of accuracy required, all location classes were considered for analysis, unless the location proved to be implausible according to predicted maximum flying speeds (80km/h) by Pennycuick (1982). Distances were calculated using an equidistant azimuthal (south pole) projection. The ratio of total distance covered to maximum range from the colony was calculated to give an indication of the convolutedness of the path. As grey-headed albatrosses dive mostly during the day and mainly rest on the surface of the water during the night (Huin & Prince 1997), we considered plots when birds moved at a speed of <10 km.h^{-1} during daylight hours as indicative of concentrated foraging in an area. This is consistent with theoretical models that predict that high frequency of prey capture leads to an increase in complexity of movement and decreased velocity in order to maximise search effort in profitable areas (Knoppien & Reddingius 1985, Benhamou & Bovet 1989).

Bird movements were analysed in relation to monthly remote-sensed sea surface temperature data available from Integrated Global Ocean Services System (IGOSS). The extent of thermal zones was estimated using information from Lutjeharms & Emery (1983), Lutjeharms *et al.* (1985) and Belkin & Gordon (1996). These authors recognize three major thermal fronts within our area of interest in the South Indian Ocean. These fronts divide the ocean into four major thermal zones: 1) the Antarctic Zone (AZ) which covers the area between the Antarctic Divergence and the Antarctic Polar Front (APF), 2) the Polar Frontal Zone (PFZ) which lies between the APF and the Sub-Antarctic Front (SAF), 3) the Sub-Antarctic Zone (SAZ) which lies between the SAF and the Sub-Tropical Front (STF), and 4) and the Sub-Tropical Frontal Zone (STFZ) which is the broader extent of the STF. The APF is not well expressed at the surface but it lies between the 3 and 5°C isotherms. The SAF has a core temperature of 8°C, while the STF has a core temperature of 14°C in the African sector of the South Indian Ocean. In this study we loosely define the AZ as the area south of the

4°C isotherm, the PFZ as the area between the 4°C and 8°C isotherms, the SAZ as the area between the 8°C and 12°C isotherms, and the STFZ as the area between the 12°C and 16°C isotherms. Waters to the north of the 16°C isotherm are referred to as the Sub-Tropical Zone (STZ) (see Fig. 4.3 for isotherms).

Diet sampling

Thirty stomach samples were collected at two separate periods during chick rearing: 25 January to 5 February (early chick-rearing), 8 March - 16 April (late chick-rearing). Chicks were sampled immediately after they had been fed and their parents had left the colony. They were induced to regurgitate by inverting them over a bucket, while gently squeezing their stomachs and massaging their necks. The total mass of the sample was measured immediately, after which the liquid portion was drained off and the mass of the solid portion determined. The solid portion was then divided into prey categories, which were weighed separately. All items that could assist in the identification of species were removed and stored appropriately. These were identified with the help of Norbert Klages, at the Port Elizabeth Museum.

Information on longline fishing effort

Pelagic longline effort (mostly for tuna) in the southern Indian Ocean was taken from Tuck and Bulman (2001) or supplied directly by G.N. Tuck (CSIRO Marine Research, Hobart, Australia). Positions of all lines set by sanctioned Patagonian toothfish longline fishing vessels within the South African EEZ were made available by the South African Directorate of Marine and Coastal Management. I have used the 95% probability contour of a kernel home range analysis (Worton 1989) of all sets as the boundary of the toothfish fishing zone.

All statistical analyses follow Zar (1984). Statistical significance was assumed at the $P \leq 0.05$ level, however, due to the relatively small sample sizes involved in this type of work, all analyses with $P \leq 0.1$ are reported.

RESULTS

Duration of foraging trips and chick provisioning

During the early chick-rearing stage, a total of 113 feeding events was observed at 16 nests. On average chicks were fed every 1.64 days. The average duration of 23 individually-timed foraging trips (15 from birds carrying devices and eight from undisturbed birds) was 3.45 days. The average for birds carrying devices was 3.66 days, while for undisturbed birds it was 3.05 days. This difference was not significant ($U = 50$; $P = 0.54$).

The frequency distribution of the duration of foraging trips during the early chick-rearing phase appeared to be bimodal (Fig. 4.1), with seven trips (30%) of ≤2 days in length (average = 19.1 hrs) and 16 trips of >2 days (average =112.2 hrs). Males made a higher proportion of very short (≤2 days) and very long (≥7days), while females made a higher proportion of medium duration foraging trips (3-6 days). However, this result was not statistically significant ($\chi^2 = 1.97$; $P = 0.16$).

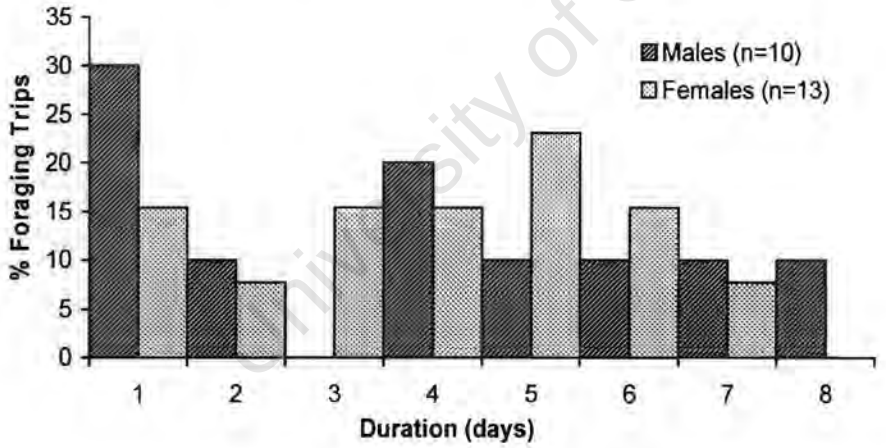

Figure 4.1 Frequency distribution of individually timed foraging trips of grey-headed albatrosses breeding on Marion Island during the early chick-rearing period.

Flight path parameters

During incubation, tracked birds ranged 1 053–4 060 km from the colony and covered total distances of 6 600-17 870 km, during a single foraging trip (Table 4.1). During the early chick-rearing stage foraging trips were significantly shorter in duration ($t = 7.54$; $P < 0.01$), range ($t = 3.3$; $P < 0.01$) and total distance ($t = 4.07$; $P < 0.01$) than

during incubation (Table 4.1). During chick-rearing birds only moved 70-1812 km from the island and covered total distances of 180-4737 km in a single foraging trip. The ratio of distance/range was also smaller for during chick-rearing (t = 2.21; P = 0.06), indicating that foraging trips were less convoluted and more directed.

Table 4.1 Flight path parameters of grey-headed albatrosses tracked by PTTs and GLSs from Marion Island during the incubation and early chick-rearing stages.

Paramater	Incubation Mean ± SD (Range)	Early Chick-Rearing Mean ± SD (Range)	t Stat (Incub. vs Chick)	P
No. of Individuals	4 (all PTT)	6 (2PTT,4 GLS)		
No. of Foraging Trips	4 (all PTT)	14 (6PTT, 8GLS)		
Duration (days)	19.25 ± 6.99 (10 - 26)	3.88 ± 2.15 (0.5 – 7.1)	7.54	<0.01
Range (km)	2 182 ± 1408 (1 053 – 4 060)	722 ± 538 (70 – 1 812)	3.30	<0.01
Distance (PTTs Only) (km)	12 210 ± 5 635 (6 600 – 17 870)	2 420 ± 1 866 (180 – 4 737)	4.07	<0.01
Av. Speed (PTTs Only) (km/h)	19.4 ± 6.8 (12.1 – 27.7)	22.6 ± 6.1 (13.4 – 27.7)	-0.79	>0.1
Distance/Range (PTTs Only)	5.88 ± 4.15 (2.6 – 10.5)	2.39 ± 0.28 (2.1 – 2.8)	2.21	0.062

The frequency distribution of maximum foraging ranges (Fig. 4.2) shows that females made a higher proportion of medium distance foraging trips (400 – 800 km) (χ^2 = 2.8; P = 0.09), while the maximum foraging range of males was more variable than females (F = 0.306; P = 0.09) (i.e. males made more very short and very long foraging trips).

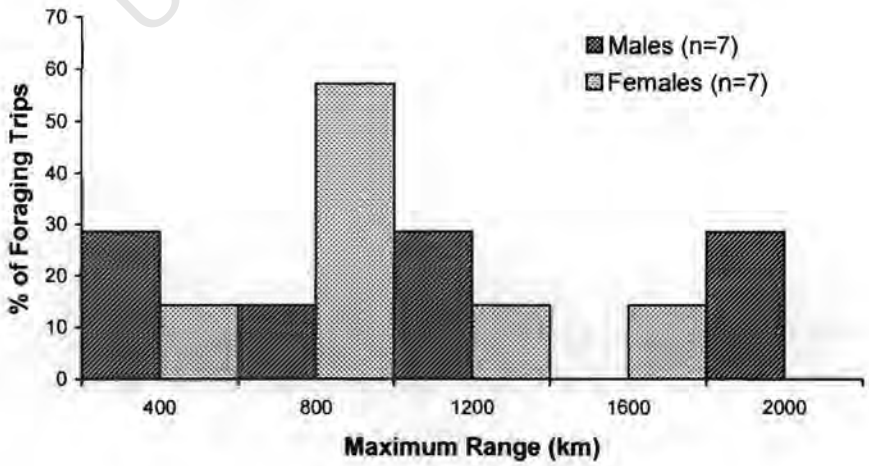

Figure 4.2 Frequency distribution of the maximum foraging ranges of grey-headed albatrosses tracked by PTTs and GLSs during the early chick-rearing period.

Birds moved far more during the day (either travelling or searching) than the night. Most of the night (83% during incubation and 75% during chick-rearing) was spent moving at speeds of <10 $km.h^{-1}$. Huin & Prince (1997), used depth recorders to show that these birds rested on the surface for most of the night (i.e. they were not feeding).

Foraging movements in relation to thermal fronts

During incubation all four birds initially left the island in a westerly direction. Three birds (two females and one male) then moved northwards and foraged in the warmer waters of the STF and SAZ (Fig. 4.3), while the fourth (a male) foraged mostly in the PFZ and AZ.

The two females moved rapidly in a north westerly direction before foraging in the SAZ and STFZ south of Africa. Unfortunately the device of the female foraging in the SAZ stopped working after four days in this area. The other female moved 1400km further westwards before again foraging in the STFZ and SAZ. The first male also moved rapidly northwards to the STFZ where it foraged extensively, before following the 12°C isotherm westwards to Amsterdam Island where it proceeded to forage for seven days. Unfortunately, this bird lost its device at this point. The second male displayed very different foraging behaviour to the previous three birds, following a highly erratic flight path confined almost entirely to waters of the PFZ and AZ.

During the early chick-rearing stage, all 14 tracked foraging trips were confined to the PFZ and AZ in the quadrant to the south west of Marion Island (Fig.4.4 a and b). Two main types of foraging trips can be identified in Fig 4.4 a and b: short foraging trips during which birds ranged 80-145 km from the island, and long foraging trips, during which birds ranged 414-1812 km from the island. The PTT-tracked female made two long foraging trips while the male alternated long and short foraging trips (Fig. 4.4a). Three of the four long satellite-tracked foraging trips showed intensive foraging activity in a very specific area (*c.* 53°S and 33°E), *c.* 900 km to the south west of the island. On one occasion the PTT-tracked male and female foraged within 100km of each other on the same day. The male again foraged in this area on its following long foraging trip. One of males carrying a GLS also foraged in this area. Both satellite-

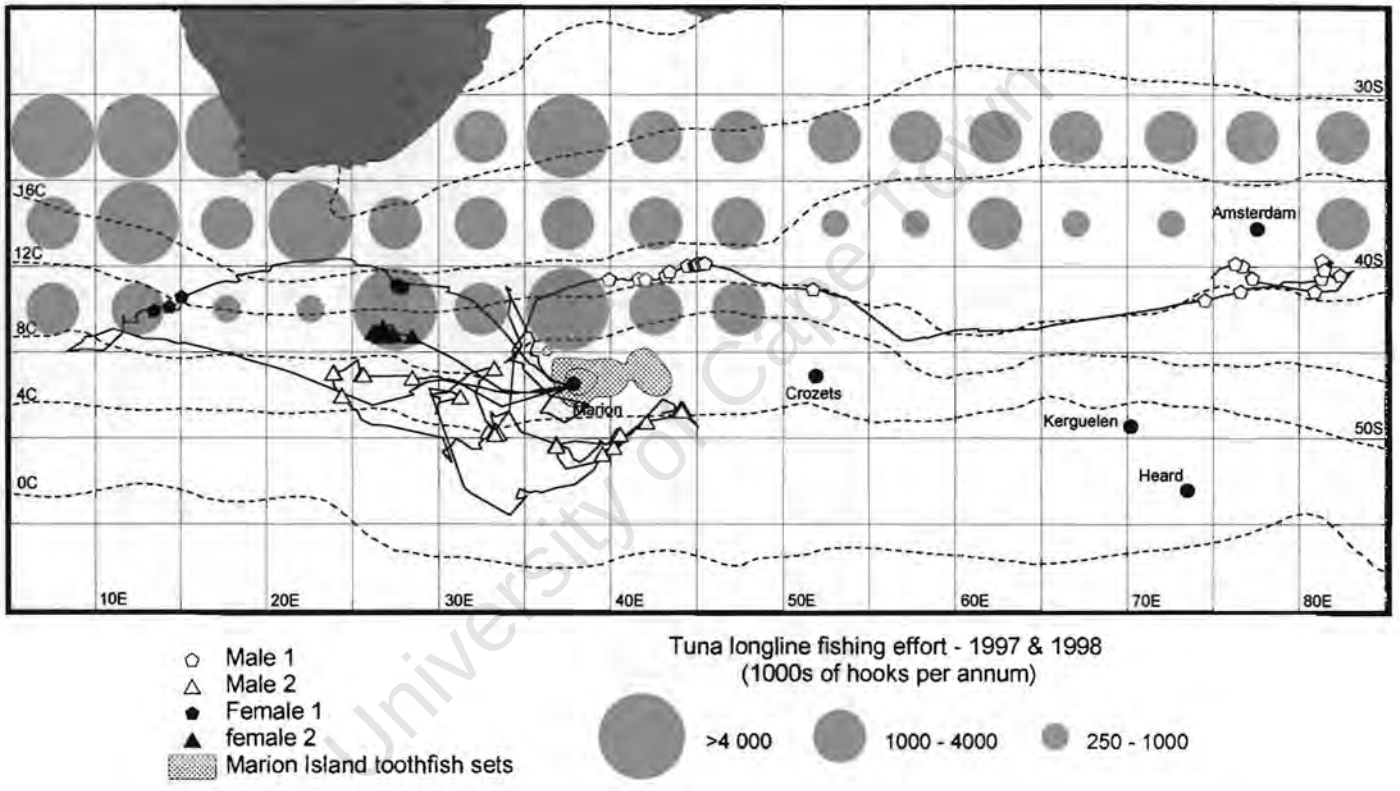

Figure 4.3 Foraging movements of grey-headed albatrosses tracked by PTTs from Marion Island during the incubation stage in relation to sea surface temperature and longline fishing effort. Symbols indicate positions at which birds were moving at < 10km/h during the daylight hours, indicating probable foraging areas.

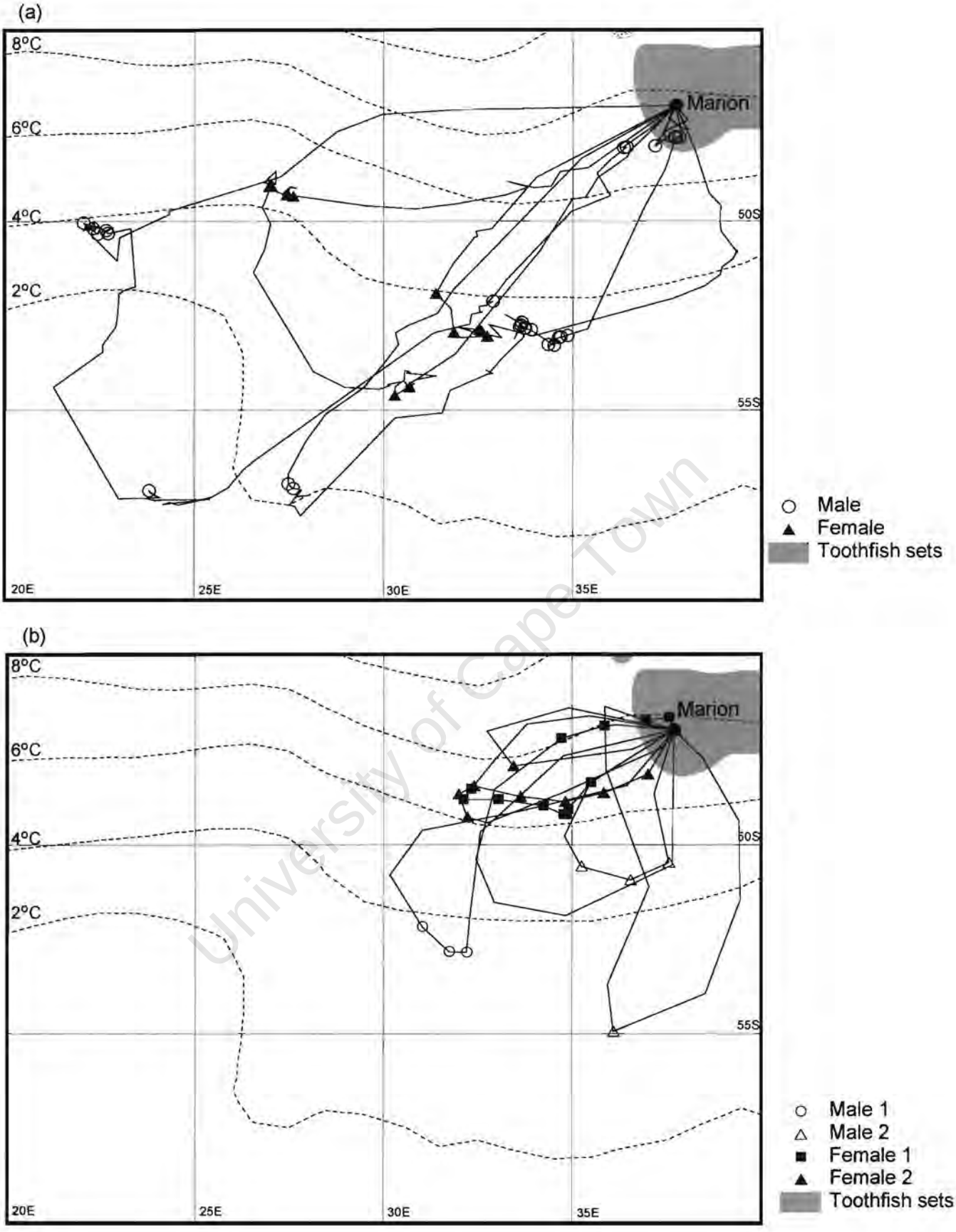

Figure 4.4 Foraging tracks of grey-headed albatrosses breeding on Marion Island, during early chick-rearing: (a) six foraging trips from two individuals carrying PTTs and (b) nine foraging trips from four individuals carrying GLSs. The symbols indicate probable foraging areas and were taken as the positions at which the birds moved <10km/h since their previous location.

tracked and GLS tracked males tended to forage farther south than females, during long foraging trips.

Utilization of the various oceanographic thermal zones differed significantly between the incubation and early chick-rearing stages (Fig. 4.5). During the early chick rearing stage, tracked birds spent significantly more time in the PFZ (t = 3.58; P = 0.007), while during incubation stage birds spent more time in the STFZ (t = 1.96; P = 0.09) and SAZ (t = 1.84; P = 0.1).

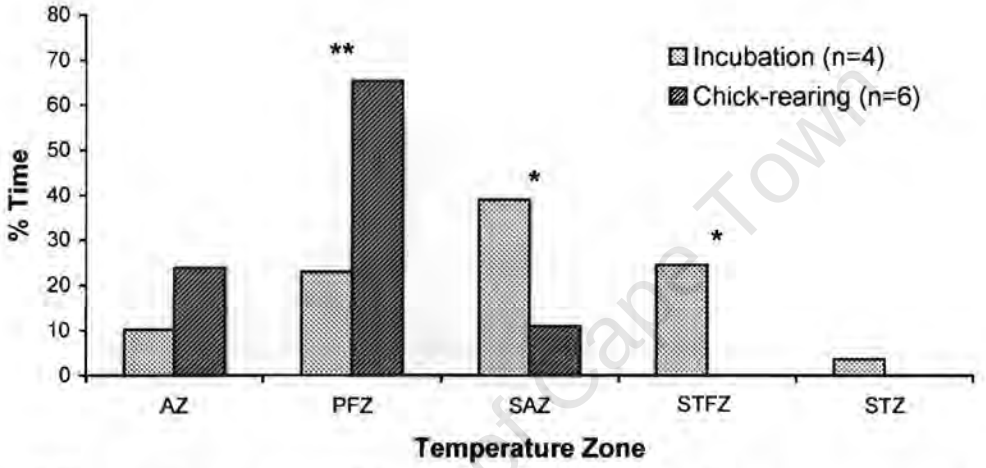

Figure 4.5 The average proportion of time spent in various sea surface temperature zones by grey-headed albatrosses tracked from Marion Island. AZ = Antarctic Zone, PFZ = Polar Frontal Zone, SAZ = Sub-Antarctic Zone, STFZ = Sub-Tropical Frontal Zone, STZ = Sub-Tropical Zone. * = P (T test) ≤ 0.1 and ** = P (T test) ≤ 0.05.

Diet

The diet composition is detailed in Table 4.2. Fish (59%) and cephalopods (32%) were the major constituents of the solid fraction, giving a fish:cephalopod ratio of 1.86. Crustaceans only contributed 3% by drained mass.

The most frequently occurring fresh prey species was the ommastrephid squid *Martialia hyadesi* (occurring in 27% of samples), followed by the decapod shrimp *Pasiphaea scotiae* (23%) (Appendix 4.1). Fresh specimens of the fish *Magnisudis prionosa* and the amphipod *Themisto gaudichaudii* occurred in 20% of the samples. Fresh squids were recorded more frequently in samples taken from the late chick-rearing stage compared to those taken during early chick-rearing (χ^2= 4.7; P = 0.03). This was mainly due to the appearance of *M. hyadesi* in 42% of the samples taken

during the late chick-rearing stage. This was significantly different from the early chick-rearing stage (χ^2 = 6.3; P = 0.01). Amphipods also occurred more frequently during the late chick-rearing period (χ^2 = 2.7; P = 0.09).

Table 4.2 Composition of grey-headed albatross diet samples collected at Marion Island, Jan-March 1998.

Parameter	Mean ± SD (g)	Range (g)	% of Total mass
	Summary data		
Total mass	722±294	302-1432	
Liquids	353 ± 244	0-934	49
Solids	368 ± 155	123-692	51
	Prey categories		% of solid fraction
Fish	220.1±210.2	0-680	59
Squid	114±109.5	0-409	32
Crustacean	6.3±11.6	0-59	2
Other	25.1±74.2	0-328	7

Only two specimens that could have originated as offal from toothfish longline vessels were found, both in the same sample. These were two specimens of the family Macrouridae, which are a major bycatch species in the toothfish industry. No known longline bait species were found. Man-made litter, which included a squid jig and two hard pieces of plastic, were found in 10% of the samples.

Spatial overlap with known longline fishing grounds

Incubation

The extensive use of the STFZ and SAZ during this stage brought these birds into areas of intensive tuna longline fishing (Fig. 4.3). After leaving the island, both females moved directly north-westwards to forage in the grid square 40-45°S and 25-30°E, an area of very high tuna longline effort (> 4 million hooks annually). One of the tracked males utilised the STFZ further to the east, encountering areas of moderate tuna longline fishing effort (1-4 million hooks annually) between 40°E and 50°E. The second male remained south of the main tuna longline fishing grounds. On average, the four birds spent 47% of their total time at sea within the 5° grid squares which supported >1 million hooks (Table 4.3). During the incubation stage, tracked birds

moved rapidly to and from the island, spending only 0.7% of their time within the boundary of known Patagonian toothfish longline sets (Table 4.3).

Early chick-rearing stage

During this stage, tracked birds (n = 6) made a total of 14 foraging trips exclusively to the south west of Marion Island, totally avoiding the tuna longline fishing areas. However, the satellite-tracked birds spent 11% their total time at sea within the boundary of known Patagonian toothfish longline sets (Table 4.3). Although most toothfish sets were to the north east of the island, some fishing took place to the south, within 200 km of the island. It is in this area that the PTT-tracked male foraged during three of its four foraging trips (Fig. 4.4a). On two of these occasions the bird was engaged in a short foraging trip (<24 hrs) while on the third, the bird foraged here briefly on the outward leg of a longer foraging trip (6 days). No licensed Patagonian toothfish longline vessels were in this area at the time of deployment.

Table 4.3 The proportion of time spent within known tuna and toothfish longline fishing grounds by grey-headed albatrosses tracked from Marion Island.

Fishing Area	Incubation			Early Chick-rearing		
	Males (2 PTTs)	Females (2 PTTs)	All (4 PTTs)	Males (1 PTT, 2 GLSs)	Females (1 PTT, 2 GLSs)	All (2 PTTs, 4 GLSs)
Tuna [1] (PTTs and GLSs)	19.4	75.3	47.3	0	0	0
Toothfish [2] (PTTs only)	0.61	0.87	0.74	16.7	6.2	11.4

[1] Tuna fishing areas grounds are represented by 5° grid squares in which >1 million hooks in either 1997 or 1998 (Tuck & Bulman 2001).
[2] Toothfish fishing grounds are represented by the 95% probability boundary of a kernel home range analysis of all lines set during 1996-1998.

Differences between males and females

During incubation the two tracked females spent 75% of their time foraging within areas of high tuna longline fishing activity (i.e. supporting >1 million hooks in either 1997 or 1998). The two males only spent 19% of their time in these areas (Table 4.3). During the early chick-rearing stage the PTT-tracked male spent 17% of its total time at sea within the boundary of toothfish longline sets, while the female only spent 6% of its time in this area (Table 4.3). This was due to the male foraging within the toothfish fishing zone during its two short foraging trips and on the outward leg of one of its long foraging trips (Fig 4.4a).

DISCUSSION

The results of this study have added greatly to our understanding of the foraging ecology of grey-headed albatrosses breeding at Marion Island. This is turn has allowed us to gain an understanding of both the nature and scale of interactions with longline fishing operations within their potential foraging range. Furthermore, a preliminary understanding of gender differences in the foraging strategy that could contribute towards sex-biased mortality in longline fishing operations was also developed.

Foraging movements and ecology

The foraging movements of grey-headed albatrosses during the incubation and early chick-rearing stage showed substantial differences. Trips made during the early chick-rearing stage were shorter (in duration, range, and total distance), and more directed (lower ratio of total distance:maximum range) than during incubation. These differences are expected because foraging behaviour during the incubation phase is primarily aimed at the adult regaining its body condition for the next incubation (and thus starvation) shift, whereas foraging behaviour during chick rearing is a constant compromise between provisioning the chick and maintaining the body condition of the parent (Weimerskirch *et al.* 1994). Time constraints imposed by the need to feed the chick at regular intervals also preclude parents from being more selective of foraging sites during early chick rearing. The mean foraging range during incubation (2182 km) recorded in this study (although from only three complete tracks) is only slightly shorter than that of incubating white-chinned petrels *Procellaria aequinoctialis*, which have the longest mean foraging range reported for any seabird (2390 km; Weimerskirch *et al.* 1999). The bimodal distribution of foraging trip duration recorded during early chick-rearing, has also been noted for grey-headed albatrosses at Campbell Island (Waugh *et al.* 1999), as well as several other procellariiforms (e.g. Weimerskirch *et al.* 1994; Weimerskirch *et al.* 1997).

These differences in foraging ranges between incubation and early chick-rearing led to substantial differences in the utilization of the various oceanographic thermal zones. During incubation the STFZ and SAZ was preferred, while during the early

chick-rearing period the PFZ and AZ were utilized exclusively. The use of the PFZ by grey-headed albatrosses during the chick rearing period is consistent with other studies on grey-headed albatrosses, conducted at South Georgia (Prince *et al.* 1997) and Campbell Island (Waugh *et al.* 1999). However, my results present the first foraging tracks of incubating birds, and show a markedly different foraging strategy during this stage. This preference for warmer subtropical waters during incubation, and colder Antarctic waters to the south during chick-rearing, is similar to that recorded for white-chinned petrels at the nearby Crozet islands (Weimerskirch *et al.*, 1999), which have a similar breeding season and are also killed in large numbers by longline fishing operations (Barnes *et al.* 1997, Gales *et al.* 1998, Ryan & Boix-Hinzen 1998, Chapter 1).

Although tracking during chick-rearing was restricted to the early part, diet samples taken during the early and late-chick-rearing stages confirmed that the SAZ and PFZ were the predominant foraging zones throughout the chick-rearing stage. The most frequently recorded fresh prey species during the late chick-rearing stage, the ommastrephid squid *Martialia hyadesi*, is strongly associated with the Antarctic Polar Front (Rodhouse *et al.* 1992). Although little is known about the biology and distribution of the most abundant and frequently occurring fish species, *Magnisudis prionosa* (Gon & Heemstra 1990), it is commonly found in the diets of other sub-Antarctic seabirds and seals that are known to make extensive use of the PFZ (e.g. Hindell 1988, Cherel *et al.* 1996, Reid *et al.* 1996, Klages & Bester 1998). The importance of *M. hyadesi* in the diet of grey-headed albatrosses breeding at Marion Island is of conservation significance because this species has potential for commercial exploitation (Rodhouse 1997). *M. hyadesi* is the dominant squid prey (85% by mass) of grey-headed albatross populations breeding at South Georgia and Campbell Island, which also make extensive use of the PFZ during chick-rearing (Rodhouse *et al.* 1990, Waugh *et al.* 1999).

An increase in man-made litter during the past decade was detected in the diet samples. Litter items were found in 10% of samples, compared to Hunter & Klages (1989) who found no litter items in 88 samples taken in 1985 and 1987. This trend is consistent with global increases in man-made marine litter (e.g. Ryan & Moloney 1993). Albatross chicks are prone to the accumulation of large amounts of man-made

litter within the proventriculus, when litter items are repeatedly fed to them by their parents (Auman *et al.* 1998, Chapter 2). This can lead to a decrease in body condition (Ryan 1987) and possibly even starvation (Chapter 2).

Exposure to the risk of incidental mortality by longline fishing industries

The extensive use of the STFZ and SAZ during incubation (November/December) recorded in this study, brings these birds into close contact with the band of intense tuna longline fishing activity situated between 40-45°S (Fig. 4.3). This interaction was especially intense in the grid square 40-45°S and 25-30°E, where the presence of the Agulhas Front increases the intensity and productivity of the STF (Lutjeharms & Emery 1983). During 1996, 21.5% of the effort took place during the first and fourth quarters of the year (i.e. October to March), which coincides with the main part of the grey-headed albatross breeding season (Tuck & Polacheck 1997). However, prior to 1976, *ca.* 50% of effort took place during these months. This decrease in effort during the austral summer months is largely due to the imposition of catch quotas. The Japanese quota year begins in April and many vessels will thus have filled their quotas by the time summer arrives. However, the decrease in Japanese tuna fishing effort in the summer months, results largely in a spatial contraction, with the most intensely utilized areas, still being fished during the austral summer months (Polacheck & Tuck 1995).

Due to a limited observer program on pelagic tuna longline vessels in international waters, little is known about seabird bycatch rates in this area. However, Japanese observers reported 84 grey-headed albatrosses killed during fishing operations south of Africa between 1992-1996 (at a rate of 0.045 birds per 1000 hooks) (Ryan & Boix-Hinzen 1998). Our data indicate that grey-headed albatrosses breeding at Marion Island show a high degree of spatial overlap with this fishery during the incubation stage and are thus are at high risk of incidental mortality during this stage. Increased tuna longline fishing effort during the mid-1990s could thus have had an impact on the Marion Island population.

During the early chick-rearing stage, our tracked birds moved south of the island, avoiding the tuna longline fishing grounds. However, PTT-tracked birds spent

significantly more time within the boundaries of the local Patagonian toothfish longline sets during this stage, thus placing themselves at risk of incidental mortality by this fishery. The potential for interaction with this fishery was clearly demonstrated, with foraging activity recorded within the boundaries of this fishery during two short foraging trips (<2 days) and on the outward leg of a long foraging trip (Fig.4.4a). Individually-timed foraging trips also showed that these short trips (<2 days) were a common feature (30% of all trips) of the foraging strategy during the early chick-rearing stage.

These data are consistent with the actual mortality rates of grey-headed albatrosses recorded by licensed vessels during 1996/97. Catch rates of grey-headed albatrosses, and specifically males, were far higher during chick-rearing period than the incubation period (Chapter 1, Figure 1.3). No seasonal variation in fishing effort exists in the Marion Island toothfish industry (Ryan & Watkins 1999). Although Ashford *et al.* (1995) and Prince *et al.* (1997) both report grey-headed albatrosses at South Georgia as being shy of toothfish vessels and therefore at low risk from this fishery, C.Boix-Hinzen (pers. comm.) reports grey-headed albatrosses as being present at all daylight sets around Marion Island during May 1997, and as being the most active species. Cherel *et al.* (1996) also reports grey-headed albatrosses successfully competing for toothfish longline baits in Kerguelen waters.

The absence of toothfish bait species in our diet samples was initially surprising, given the high level of mortality of grey-headed albatrosses recorded on licensed toothfish vessels during their first season. However, after initially setting lines both at day and at night during the first season, licensed vessels have been restricted to setting lines during the hours of darkness since the second season (the time of this study). This mitigation measure has reduced the bycatch of albatrosses drastically (Chapter 1). The results from this study also indicates that grey-headed albatrosses are far less active during the night (spending *c.* 75% of the night virtually stationary) and thus support this mitigation measure.

Grey-headed albatrosses breeding on Marion Island are thus at higher risk of incidental mortality in the local toothfish industry during the early chick-rearing stage than during incubation. This risk is mainly during short foraging trips (<2 days) and

can be virtually eliminated if lines are set exclusively during the hours of darkness. However, illegal longline fishing operators show scant regard for these regulations and could therefore have a severe impact on the Marion Island grey-headed albatross population.

Decreased adult survival due to incidental mortality by longline fishing leads to complex effects on the demographics and productivity of albatross populations (e.g. Croxall *et al.* 1990, Weimerskirch *et al.* 1997a), and may not be immediately noticeable as a change in the number of breeding birds. This study has demonstrated the vulnerability of the breeding population of grey-headed albatrosses on Marion Island to incidental mortality by two different and spatially-disjunct longline fisheries, during incubation and chick-rearing. Although the effect of this mortality has not been detected in annual counts of the breeding population (due to the high annual variation in numbers breeding), these methods are inadequate for assessing short term changes (<10 years) in biennial breeding albatross populations (Chapter 6). Increased adult mortality due to a recent increase the tuna longline effort in the Southern Indian Ocean and the development of a Patagonian toothfish longline fishery close to the island, may have already led to complex effects on the demography of this population. This in turn may lead to a decline in the annual breeding population in the future, which once detected, could take a long time to stabilise (Moloney *et al.* 1994).

Differences between males and females

Although our limited data should be treated with caution, the differences in the foraging behaviour of males and females that we recorded could contribute towards sex-biased mortality of grey-headed albatrosses in the longline fisheries. During the incubation phase satellite-tracked females spent significantly more time in the intense tuna longline fishing areas south of Africa, than males. This will result in a higher level of exposure to the risk of incidental mortality for females. No data on the gender composition of grey-headed albatrosses killed by the tuna longline fishery in pelagic waters south of Africa are available. However, female adult wandering albatrosses from Marion Island (Chapter 7) and the Crozet Islands (Weimerskirch *et al.* 1997a) have a lower survival rate than their male counterparts. A higher degree of exposure to the risk of incidental mortality by tuna longline fisheries has been implicated as the main reason for this difference (Weimerskirch *et al.* 1997a).

During the chick-rearing stage the PTT-tracked male spent more time foraging within the boundaries of the local toothfish longline sets than the female. This was largely due to the male making two short foraging trips (<2 days), within these boundaries. Individually-timed foraging trips of a larger sample of birds, showed that males made a higher proportion of these short foraging trips (<2 days). This is consistent with studies on wandering albatrosses on Marion Island (Chapter 3) and on Crozet Islands (Weimerskirch *et al.* 1997b), which showed that males spent a higher proportion of their time engaged in short foraging trips than females. It is thus possible that these subtle differences in foraging strategy in combination with physical attributes such as aggression when competing for baits, can account for the male-biased mortality observed in the Prince Edward Island Patagonian toothfish industry during the first season (Chapter 1).

Because grey-headed albatrosses are largely monogamous (96% breed with the same mate in successive attempts; Prince *et al.* 1994), sex-biased mortality of breeding adults will obviously have added costs to the population, other than the direct cost of decreasing the number of breeding birds. Jouventin *et al.* (1999) estimated that remating for the monogamous wandering albatross exerts an average reproductive cost of 15% of the lifetime reproductive success. Gender differences in foraging strategy and incidental mortality by longline fishing vessels should thus be closely monitored and researched, and the added cost of sex-biased incidental mortality should be taken into account when assessing the detrimental effects on these populations.

Appendix 4.1 The frequency of occurrence of fresh prey items identified in grey-headed albatross diet samples taken during early (January 1998) and late (March and April 1998) chick-rearing, from Marion Island.

Taxa	Early chick-rearing (n = 11) % (n)	Late chick-rearing (n = 19) % (n)	Total % (n)
FISH	63.6 (7)	63.2 (12)	63.3 (19)
Family Macrouridae			
Cynomacrurus piriei	9.1 (1)		3.3 (1)
Family Myctophidae	18.2 (2)	5.3 (1)	10.0 (3)
Electrona subaspera	9.1 (1)		3.3 (1)
Gymnoscopelus piabilis	9.1 (1)		3.3 (1)
Unid. Myctophidae		5.3 (1)	3.3 (1)
Family Paralepididae			
Magnisudis prionosa	18.2 (2)	21.1 (4)	20.0 (6)
Family Photichthyidae			
Photichthys argenteus		10.5 (2)	6.7 (2)
Unidentified Fish	27.3 (3)	36.8 (7)	33.3 (10)
SQUID	27.3 (3)	68.4 (13)	53.3 (16)
Family Chiroteuthidae			
Chiroteuthis sp.	18.2 (2)		6.7 (2)
Family Histioteuthidae			
Histioteuthis eltaninae		5.3 (1)	3.3 (1)
Family Neoteuthidae			
Alluroteuthis antarctica		5.3 (1)	3.3 (1)
Family Ommastrephidae			
Martialia hyadesi		42.1 (8)	26.7 (8)
Family Onychoteuthidae			
Kondakovia longimana		15.8 (3)	10.0 (3)
Unidentified Squid	9.1 (1)	10.5 (2)	10.0 (3)
CRUSTACEANS	72.7 (8)	68.4 (13)	70.0 (21)
Order Amphipoda	9.1 (1)	36.8 (7)	26.7 (8)
Themisto gaudichaudii	9.1 (1)	26.3 (5)	20.0 (6)
Unidentified amphipods		10.5 (2)	6.7 (2)
Order Decapoda	54.6 (6)	31.6 (6)	
Austropandalus grayi	9.1 (1)	5.3 (1)	6.7 (2)
Pasiphaea scotiae	36.4 (4)	15.8 (3)	23.3 (7)
Unidentified decapods	9.1(1)	10.5 (2)	10.0 (3)
Family Euphausiacea	9.1 (1)	21.1 (4)	16.7 (5)
Euphausia superba	9.1 (1)		3.3 (1)
Unidentified Euphausiid		21.1 (4)	13.3 (4)
OTHER		10.5 (2)	6.7 (2)
Goose barnacles		5.3 (1)	3.3 (1)
Jellyfish		10.1 (2)	6.7 (2)
Mammal lung		5.3 (1)	3.3 (1)

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CHAPTER 5

Exploitation of mesoscale oceanographic features by grey-headed albatrosses *Thalassarche chrysostoma* in the southern Indian Ocean

ABSTRACT

Breeding grey-headed albatrosses *Thalassarche chrysostoma*, tracked from Marion Island (Prince Edward Islands) during November-December 1997 and January-February 1998, showed a strong association with mesoscale oceanographic features, as identified by sea surface height anomalies, in the southern Indian Ocean. During incubation most birds foraged to the north of the island at the edges of anomalies created by the Agulhas Return Current in the Sub-tropical Frontal and the Sub-Antarctic Zones. In contrast, during chick-rearing all tracked birds foraged to the south west of the island, at the edges of anomalies along the South-West Indian Ridge. Previous work in this area has shown that these anomalies are in fact eddies that are created as the Antarctic Circumpolar Current crosses the South West Indian Ridge. Diet samples taken during the chick-rearing period showed a predominance of fresh specimens of the predatory fish *Magnisudis prionosa* and the squid *Martialia hyadesi*. Myctophid fish and amphipods (specifically *Themisto gaudichaudii*), both known prey of *Martialia hyadesi*, were also well represented in the diet. Diet samples taken from tracked birds, showed birds feeding at edges of positive anomalies, returning with fresh specimens of *Magnisudis prionosa* and *Martialia hyadesi*. Predatory fish and squid are thus presumably concentrated at these features. Eddies formed at the South West Indian Ridge have also been shown to drift closer to Marion Island, within the foraging range of penguins and seals breeding on Marion Island. These mesoscale oceanographic features may be important in enabling globally significant populations of seabirds and seals to breed at the Prince Edward Islands.

INTRODUCTION

Pelagic seabirds, and especially albatrosses, display an extreme life history. They have low reproductive rates, slow chick development, delayed onset of breeding and high adult survival (Warham 1996). Lack (1968) suggested that these breeding adaptations were the result of severe limitations to the rate at which adults could provide food to their chicks. These limits arose from the sparseness, patchiness and unpredictability of marine resources as well as the large distances adults are required to travel to and from foraging areas (Ashmole 1971). It therefore follows that breeding birds should concentrate their foraging efforts in areas where resources are most predictable. Although the most preferred foraging areas should be located closest to their breeding colonies, in order to minimize time and energy required to travel to these areas, the closest foraging areas will also have the highest intra- and inter specific competition, and may also suffer local depletion first (Ricklefs 1990). Although it seems unlikely that pelagic seabirds and seals can deplete their stocks over the ocean as a whole, it seems reasonable that they are able to do this in the vicinity of their breeding colonies and at areas where prey becomes concentrated due to physical processes (Anderson & Ricklefs 1987).

Physical and biological processes in the ocean affect the distribution and abundance of plankton and nekton, which in turn affect the distribution of seabirds and marine mammals (Piontkovski *et al.* 1995, Pakhomov & McQuaid 1996). Studies have shown that seabirds are predictably concentrated at physical oceanographic features of different spatial scales, from tidal fronts through mesoscale eddies to latitudinal frontal systems, which all display increased prey availability (Haney *et al.* 1995, Pakhomov & McQuaid 1996, Rodhouse *et al.* 1996, Hunt *et al.* 1999). Once at an area of enhanced biological productivity, procellariiforms may use odor trails or visual clues to locate concentrations of prey (Nevitt 1999).

Albatrosses living in the Southern Ocean are largely reliant on pelagic fish and squid (Cherel & Klages 1997). These prey items are patchily distributed and very little is known about the biological and environmental parameters that govern their distribution (Cherel & Weimerskirch 1995). In this paper I demonstrate how grey-headed albatrosses *Thalassarche chrysostoma*, breeding at sub-Antarctic Marion

Island, are able to exploit mesoscale oceanographic features 100s to 1000s of kilometers from their breeding locality, resulting from interactions between current systems and local bathymetry. In an attempt understand more about the ecology of these oceanographic features, I describe the diet of these birds during the chick-rearing period, when birds showed a strong association with certain oceanographic features.

Physical environment

The Prince Edward Islands, of which Marion Island is the larger, lie in the sub-Antarctic, between the Sub-tropical Front to the north and the Antarctic Polar Front to the south (Lutjeharms & Valentine 1984). A secondary front, the sub-Antarctic Front usually lies just to the north of the island group, but all three of these fronts exhibit considerable temporal changes in their latitudes (Lutjeharms 1990). Furthermore, a number of eddies of various sizes have been observed in the region, making it a complex physical environment (Ansorge & Lutjeharms submitted). Warmer, anti-cyclonic eddies have been thought to come from north of the sub-Antarctic Front and this has been borne out by the observed planktonic content of such features (Froneman *et al.* 1999). The same holds true for colder, cyclonic eddies near the islands that seem to come from south of the Antarctic Polar Front. However, these eddies are not just vehicles for carrying foreign organisms, but there is evidence that they intrinsically affect the primary productivity of their waters (e.g. Ansorge *et al.* 1999, Froneman *et al.* 1999, Perissinotto & Duncombe Rae 1990, Perissinotto *et al.* 2000) in ways that are as yet imperfectly understood.

The Sub-tropical Front has been shown to exhibit considerably enhanced levels of chlorophyll-a and zooplankton standing stock, but this enhancement seems to occur at irregular intervals (Barange *et al.* 1998). This is true both in regions where this front is strongly developed (Pakhomov *et al.* 1994) as well as where it is weaker (Barange *et al.* 1998). This enhancing effect is evident in colour observations from space (e.g. Lutjeharms *et al.* 1985, 1986, Weeks & Shillington 1994, Machu *et al.* 1999) as well as in *in situ* measurements (Allanson *et al.* 1981). However, it is not only the lowest trophic levels such as phytoplankton that are affected (Boden *et al.* 1988), but also fish and higher predators such as seabirds (Abrams 1983, 1985a, Abrams & Lutjeharms 1986, Abrams & Miller 1986).

All investigations of this type have shown that there is considerably higher mesoscale variability related to frontal systems than in other regions of the Southern Ocean. This has been shown from statistical investigations using accumulated hydrographic data (Lutjeharms & Baker 1980), from the movement patterns of surface drifters (Daniault & Menard 1985) and from satellite altimetry (e.g. Chenney *et al.* 1983). Investigations that have focused on the Sub-tropical Front have demonstrated that much of the variability here is due to the prevalence of eddies (Lutjeharms & Valentine 1988). It has subsequently been shown that the intensity of the mesoscale variability at the Sub-tropical Front diminishes from a peak south of Africa to a low value at about 70 °E (Lutjeharms & Ansorge 2001), suggesting that the prevalence and intensity of eddies at this front decrease similarly.

Secondary regions of high variability are found where the core of the Antarctic Circumpolar Current, coincident with the Antarctic Polar Front, crosses mid-ocean ridges (Lutjeharms & Baker 1980, Colton & Chase 1983). This is particularly relevant to the environment of the Prince Edward Islands. These islands lie just downstream of the South-West Indian Ridge that is crossed by the core of the Antarctic Circumpolar Current at about 50° S, 30° E (Read & Pollard 1993). Altimetric observations have shown that this specific location is a region of extraordinarily high mesoscale variability (e.g. Chenney *et al.* 1983, Wakker 1990, Snaith & Robinson 1996) that extends eastwards to the vicinity of the islands. The key question, from the point of view of marine organisms, is whether the unusually high variability at this location is due to meandering of the current, or to the spawning of eddies. Hydrographic investigation of some of the features originating here and seen in altimetry (Ansorge & Lutjeharms submitted) show that they are indeed eddies (Fig. 5.1) that are created at the ridge and subsequently move towards and past the Prince Edward Islands (Ansorge & Lutjeharms in press). It seems that this area at the South-West Indian Ridge is the major source of eddies near the islands and thus might be of considerable importance to the ecology of the region.

METHODS

Breeding grey-headed albatrosses were tracked using: 1) ST10 Platform Transmitter Terminals (PTTs) manufactured by Telonics (U.S.A.) and packaged by Sirtrack

Limited (New Zealand) (85g, 90mm×42mm×17mm), and 2) pillbox Geo-Locating Sensors (GLSs) manufactured by Driesen and Kern (Germany) (65g, 90mm×15mm diameter). The methods by which these devices fix the position of the birds are described in Chapters 3 & 4. PTTs provided successful locations at *ca* two hour intervals with a normal accuracy of <5km, while GLSs only give two positional fixes per 24 hour period with an accuracy of *ca* 40km (Wilson *et al.* in press).

The PTTs and GLSs were attached to feathers on the back of the birds (approximately between the wings) by means of adhesive tape. During late incubation (24 November to 17 December 1997) two males and two females were tracked for a total of 56 days using PTTs. Birds were captured immediately after they had been relieved of their incubation shift by their mates, and were taken to the side of the colony where the devices were attached. Attachment took 10-15 minutes. During early chick-rearing (post-brooding - 20 January to 5 February 1998) three males and three females were tracked for a total of 61 days and 15 complete foraging trips, using two PTT's (on one male and one female) and four GLSs (on two males and two females). Devices were attached to adults immediately after they had completed feeding their chick and were left on for successive foraging trips.

Movement data were plotted and spatially analysed using ARCVIEW GIS Version 3.0a (ESRI 1992). All location classes were considered for analysis, unless the location proved to be implausible according to predicted maximum flying speeds by Pennycuik (1982). Distances were calculated using an equidistant azimuthal (south pole) projection. As grey-headed albatrosses forage mostly during the day and mainly rest on the surface during the night (Huin & Prince 1997), we considered plots when birds moved at a speed of $<10 km.h^{-1}$ during daylight hours as indicative of concentrated foraging in an area. This is consistent with theoretical models that predict that high frequency of prey capture leads to an increase in complexity of movement and decreased velocity in order to maximise search effort in profitable areas (Knoppien & Reddingius 1985).

Data were analysed in relation to weekly remote-sensed TOPEX sea surface height anomaly data available from the Colorado Centre for Astrodynamics Research (CCAR) (http://www-ccar.colorado.edu). The TOPEX derived sea surface height

anomaly represents a statistical measure of temporal variations in major current systems, caused by either mesoscale eddy activities (e.g. meandering, eddy shedding), displacement of current axes or fronts, or changing speed and direction of currents (Park & Gamberoni 1995). Regions of high mesoscale variability correlate closely with either the terminal region of a major western boundary current such as the Agulhas Current or the Gulf Stream, or where the Antarctic Circumpolar Current interacts with prominent bottom topography such as in the Drake Passage or at the Crozet-Kerguelen Plateau in the Southern Ocean (Lutjeharms & Baker 1980). The launch of TOPEX/POSEIDON in 1992 has resulted in continual mapping of the global sea surface topography from which surface currents can be computed. Persistent attempts in the past using infrared imagery to ascertain the circulation pattern in the Southern Ocean have been foiled by almost continuous cloud cover. An advantage of using satellite altimetry is its ability to penetrate through cloud cover.

Thirty diet samples were collected from grey-headed albatross chicks between 25 January and 16 April 1998 (i.e. between one and four months old). Chicks were induced to regurgitate by inverting them over a bucket immediately after they had been fed by their parents. No ill effects of this procedure were noticed (all chicks appeared to be in good condition at the end of the study).

Six diet samples were taken from chicks that had been fed by tracked parents. Four of these samples yielded fresh prey items that could be related to a specific tracked foraging trip. These nests were under constant surveillance during the daylight hours and none of these chicks had been fed by the other parent for at least 24 hrs prior to our sampling. Prey items were adjudged to be fresh if the fresh pieces of the flesh of the prey item where found in the sample.

Oceanographic fronts follow Belkin & Gordon (1996) and thermal zones referred to in the text are defined as follows: The Sub-tropical Frontal Zone (STFZ) is the broader extent of the Sub-Tropical Front (STF), the Sub-Antarctic Zone (SAZ) extends from the Sub-Antarctic Front (SAF) to the southern extent of the STF, and the Polar Frontal Zone (PFZ) extends from the Antarctic Polar Front (APF) to the SAF. See Fig. 5.2 for the approximate positions of these fronts.

RESULTS

Foraging movements in relation to physical oceanographic features

During incubation, three of the four birds moved north of the island to forage in the vicinity of the STFZ and the SAF (Fig. 5.2). All three of these birds appeared to initially forage at the interface between positive and negative sea surface height anomalies. Bird 1 foraged for 3.2 days at the edge of a large positive anomaly situated in the STFZ *ca* 750 km North of Marion Island, before moving further east, tracking the string of positive and negative anomalies at the STFZ all the way to Amsterdam Island. Birds 2 and 3 moved north westwards and foraged around the same positive anomaly within the SAZ *ca* 1000 km north west of Marion Island, simultaneously. Unfortunately the device on Bird 2 stopped functioning after it had foraged here for 3.5 days. Bird 3 continued in a westerly arc, passing over the STFZ before moving slightly southwards to forage at the edge of a large negative anomaly in the SAZ. The fourth bird displayed a highly erratic foraging track restricted mostly to the Polar Frontal Zone (PFZ). However, much of its foraging activity was also concentrated around the edges of positive and negative anomalies.

During early chick-rearing, all six tracked birds moved south west of the island and foraged here on 15 separate foraging trips (Fig. 5.3). This was despite the large positive anomalies at the STFZ still being well developed. Closer inspection of the fine scale movements of PTT tracked foraging trips (Fig. 5.4) shows that most foraging activity was concentrated on the edges of two closely associated positive anomalies at *ca* 52-55°S and 30-34°E (*ca* 750 – 950 km away). Both PTT-tracked birds foraged in this area on successive foraging trips, and both were also present in the area simultaneously. Foraging activity was also recorded at the interface of anomalies located closer to the island (between 100 and 400 km away). The edge of a positive anomaly just 100 km south of the island was visited on three out of four foraging trips made by the same bird. Foraging activity during longer foraging trips

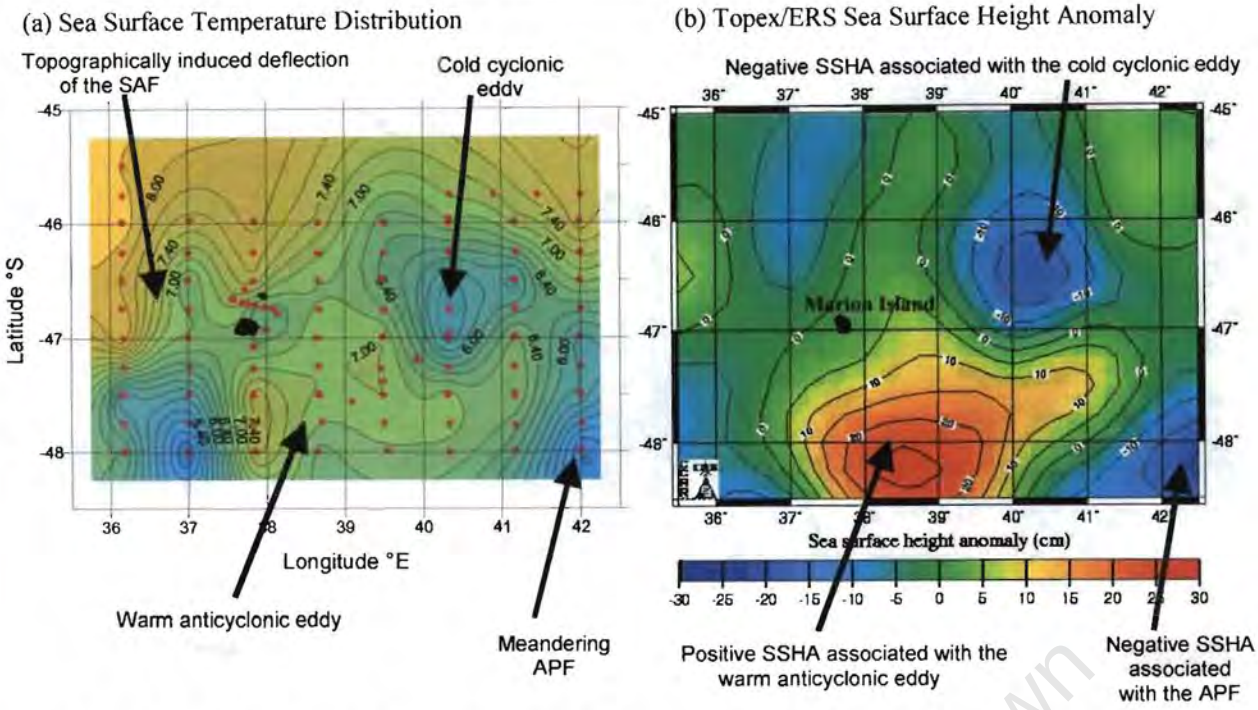

Figure 5.1 (a) Sea surface temperature distribution as determined by a hydrographic survey and (b) blended Topex/ERS Sea Surface Height Anomaly (SSHA) data. Cold cyclonic and warm anticyclonic eddies are clearly visible as positive and negative anomalies in the TOPEX/ERS altimetry (taken from Ansorge & Lutjeharms submitted).

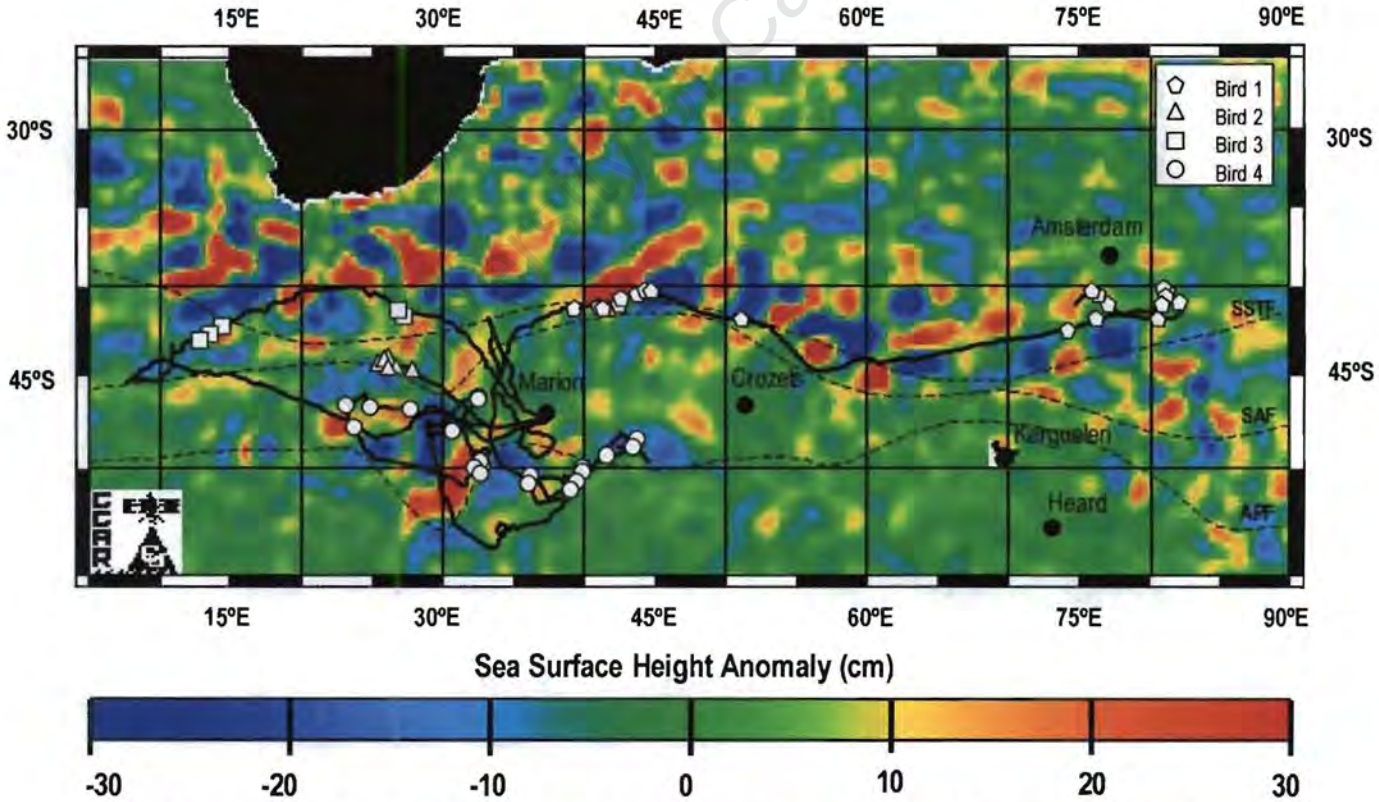

Figure 5.2 Foraging tracks of four grey-headed albatrosses tracked from Marion Island by PTTs during the incubation stage. Symbols indicate positions where birds were moving at <10km/h during the daytime (and therefore probably foraging). Dashed lines indicate the approximate positions of the major fronts (following Belkin & Gordon 1996). SSTF = Southern extent of Sub-Tropical Front, SAF = Sub-Antarctic Front, APF = Antarctic Polar Front

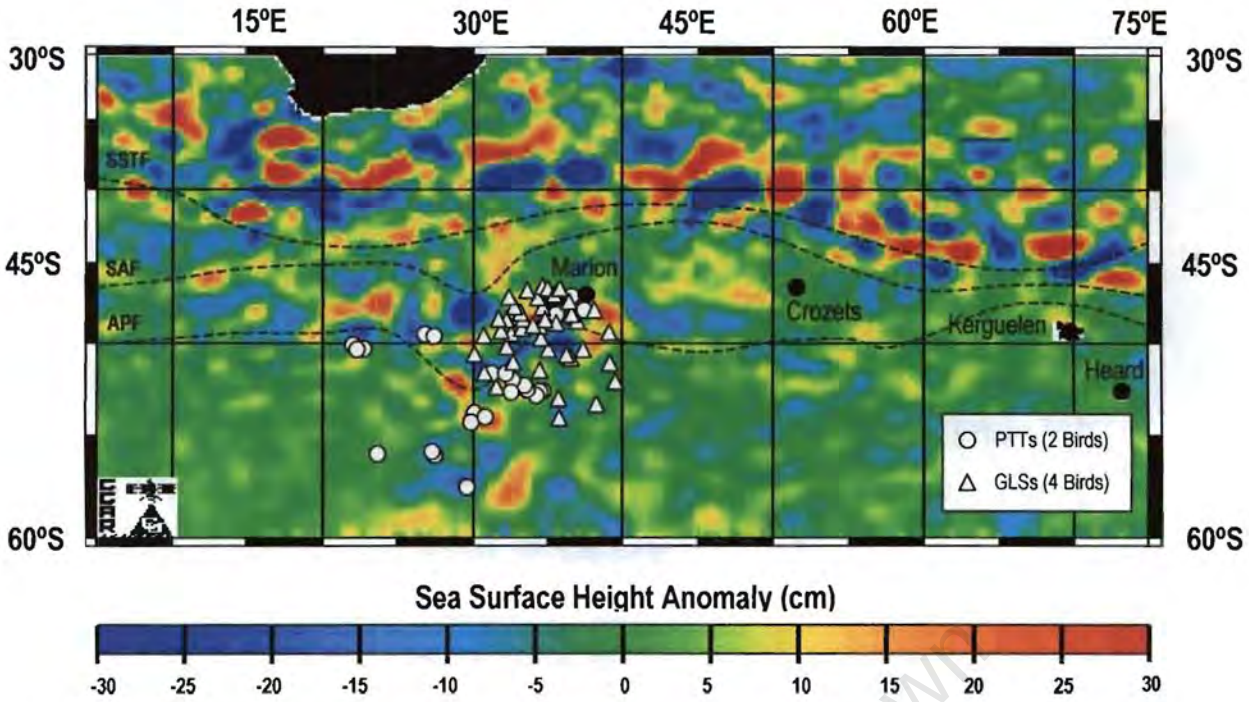

Figure 5.3 The foraging distribution of six grey-headed albatrosses tracked from Marion Island (by two PTTs and four GLSs) during the early chick-rearing stage. All GLS positions are shown, while for the PTTs, only positions where the birds were moving at <10km/h during daylight (and thus probably foraging) are shown. Other conventions as Fig. 5.2.

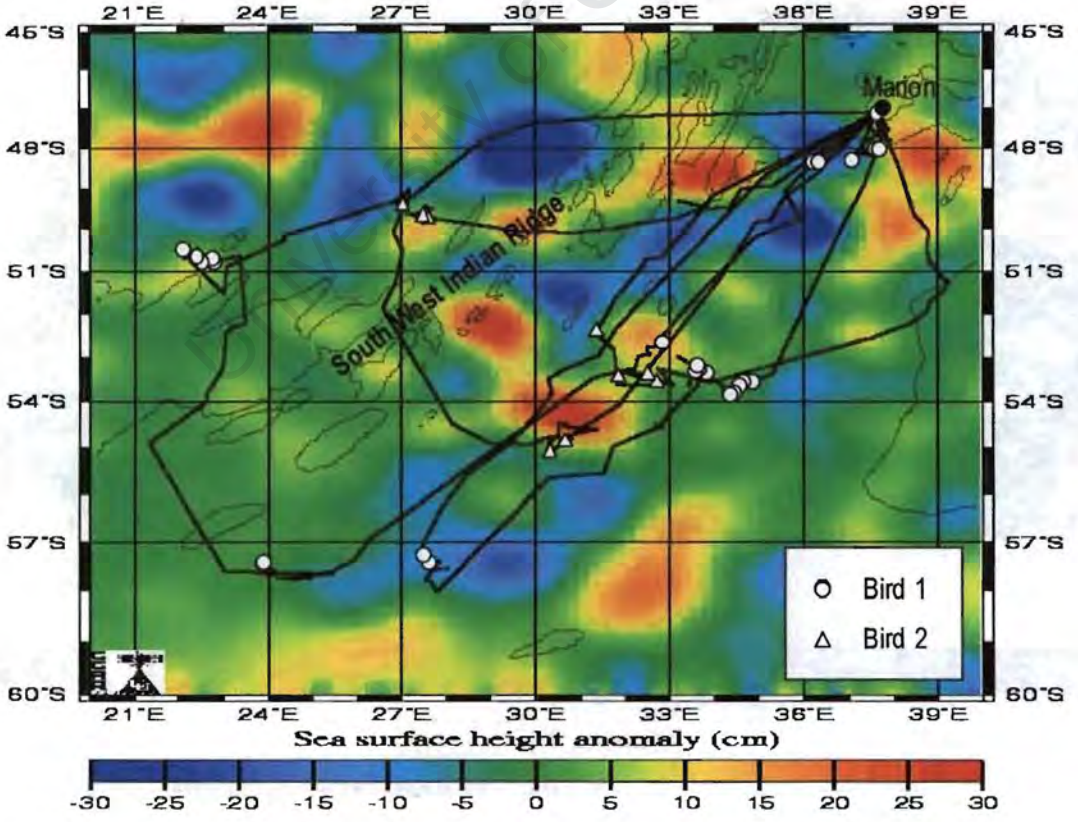

Figure 5.4 Foraging tracks grey-headed albatrosses tracked from Marion Island by means of PTTs during the early chick-rearing stage. Symbols indicate positions where the birds were moving at <10km/h during the daytime (and thus probably foraging). The dotted lines indicate the 4000m depth contour.

was concentrated around negative anomalies south of the APF (*ca* 1300 – 1800 km away). Most foraging activity was located on either side of the South West Indian ridge. Foraging trips were also very directed during this stage. Birds flew rapidly and directly to an oceanographic feature before slowing down and starting to search for food.

General diet during the chick-rearing period

Fish (59%) and cephalopods (32%) were the major constituents of the solid fraction. Crustaceans contributed only 3% by drained mass. The most common fish species, both by relative abundance and frequency of occurrence, was *Magnisudis prionosa* (Paralepididae), occurring in 30% of samples (Appendix 5.1). This was also the largest fish prey item. The smaller myctophids were the second most common family and were represented in 27% of samples.

The most frequently occurring and largest squid prey species was *Kondakovia longimana* (Appendix 5.1). However, few of these specimens were fresh and this species was probably over-represented due to large beaks being retained for longer periods in the stomachs of chicks (Berruti & Harcus 1978). The second most frequently-occurring species was the slightly smaller ommastrephid, *Martialia hyadesi*, which was found in 47% of the samples. 27% of these specimens were very fresh (beak still attached to the whole squid, the crown of arms, or embedded in the buccal mass). The smaller *Chiroteuthis sp.* and *Histioteuthis eltaninae* both occurred in 33% of the samples. *Chiroteuthis sp.* was also the most abundant squid species. The cranchiid, *Galiteuthis glacialis* was also represented in 30% of samples.

Decapod shrimps were found in 40% of the samples (Appendix 5.1). These were mostly *Pasiphaea scotiae*, while two larger *Austropandalus grayi* were also found in two separate samples. One complete *Austropandalus grayi* measured 215 mm. Euphausiids were found in 16% of the samples. All specimens that could be identified to species were *Euphausia superba*.

Large numbers of amphipods (mostly *Themisto gaudichaudii*) were found in 27% of the samples. Amphipods were also found within the stomach of an unidentified fish.

Diet items associated with particular foraging tracks

Four diet samples taken from the chicks of tracked adults yielded fresh prey items. The tracks relating to these samples are shown in Fig. 5.5. It is simple to ascribe an oceanographic feature to prey items acquired in Track 1 (Fig. 5.5a) and Track 3 (Fig. 5.5c) as these birds only foraged at a single type of feature (i.e. edges of warm eddies located about 900 and 400 km away respectively). The main prey item of both these foraging trips was the large fish *Magnisudis prionosa*. Both diet samples also contained fresh specimens of myctophids (track 1 = *Electrona subaspera* and track 3 = *Gymnoscopelus piabilis*) and the decapod shrimp *Pasiphaea scotia*.

This procedure is slightly more problematic with Track 2 (Fig. 5.5b) as this bird foraged at two main locations. However, as most foraging time was spent at the edge of a positive anomaly at the main area of variability at 53°S and 33°E and this is also the location at which bird from Track 1 (Fig. 5.5a) captured four specimens of *Magnisudis prionosa* at the same time, it is most likely that this is where the specimen of *M. prionosa* in this sample was captured. The specimen of the squid *Martialia hyadesi* could have been captured at either the warm or the cold core eddy, however given the frequency of very fresh specimens of this species recorded in our diet samples (Appendix 5.1), and the fact that Rodhouse *et al.* (1996) recorded this species in association with warm eddies at the APF in the Scotia Sea, it is most likely that this species was captured at the closer positive anomaly. *Euphausia superba* only occurs south of the APF (Pakhomov *et al.* 1994). It is thus most likely that it was this species that was captured at the cold core eddy farther south.

The bird from Track 4 (Fig. 5.5d) foraged at the edge of the positive anomaly just south of the island (*ca* 100 km away), and captured five very fresh specimens of the smaller squid *Chiroteuthis sp.* A single specimen of *Martialia hyadesi* was also recovered from this sample.

DISCUSSION

Foraging movements in relation to physical oceanographic features

Grey-headed albatrosses tracked from Marion Island showed a strong association with oceanographic features expressed as positive and negative sea surface height

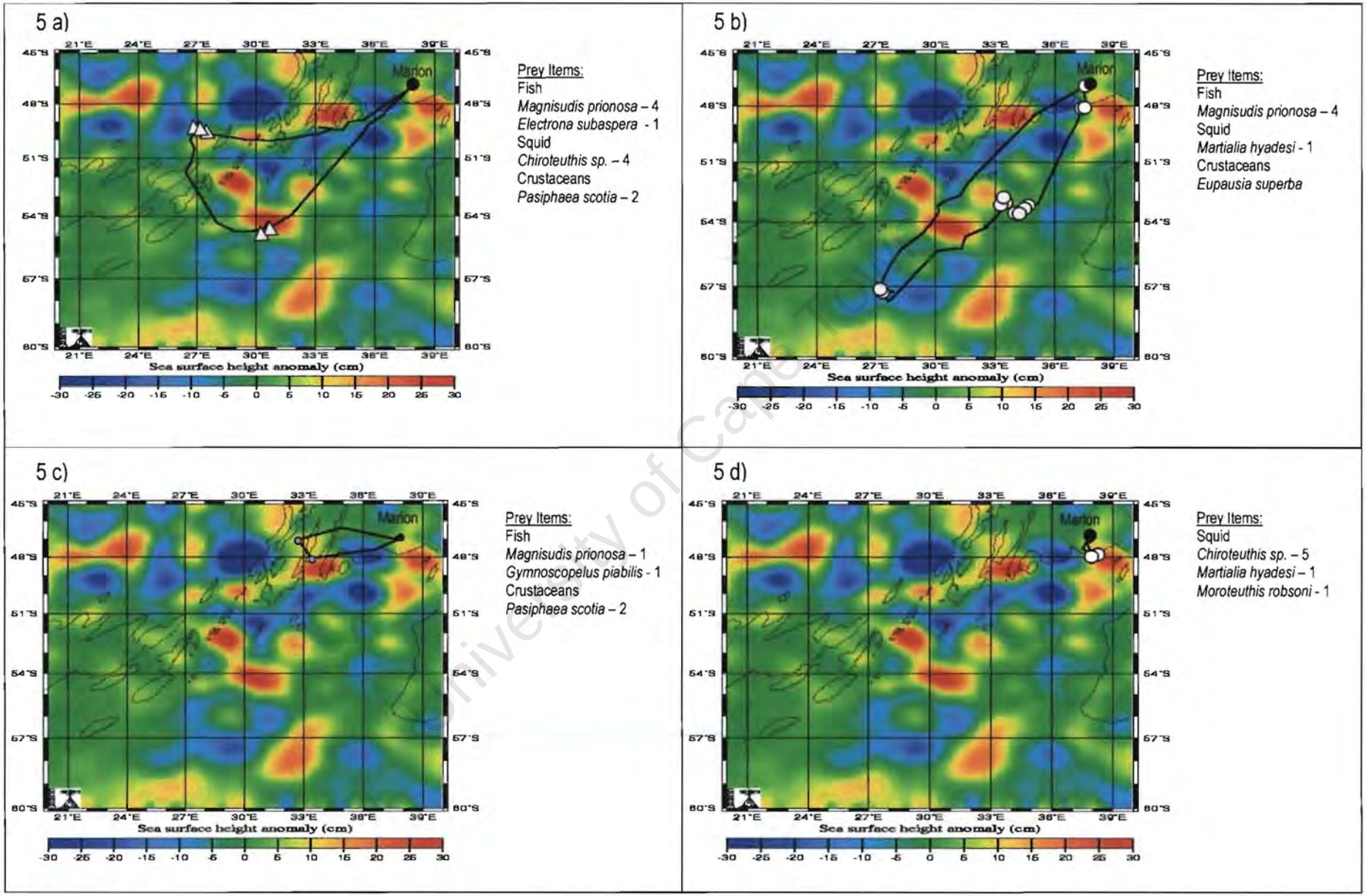

Figure 5.5 Tracks of grey-headed albatrosses tracked from Marion Island during the early chick-rearing stage. Fresh prey items recovered from the chicks are shown next to the relevant track. Symbols indicate positions where the bird was moving at <10 km/h during daylight. The dotted line indicates the position of the 4000 m depth contour.

anomalies, both during the incubation and chick-rearing stages. Interestingly, most foraging activity was concentrated at the edges of these anomalies or at the interface between positive and negative anomalies. During incubation, most birds preferred to exploit oceanographic features to the north of the island, in the STFZ and the SAZ. I cannot say unequivocally that these features, as seen in the altimetry, are eddies, but the results of previous hydrographic research in the region (e.g. Lutjeharms 1990, Lutjeharms & Valentine 1988) gives me confidence that there is a high likelihood that these are indeed eddies. These features are formed largely as a result of the interaction between the Agulhas Return Current and bathymetric features such as the Madagascar Ridge (Pollard & Read 2001).

By contrast, during chick-rearing no foraging trips were made to the STFZ (despite oceanographic features still being well developed here), but were instead made exclusively to the southwest of the island. Most foraging activity occurred at the edges of altimetric features located to the south-west of the island and either side of the South-West Indian Ridge. A number of such mesoscale features have been investigated hydrographically (Ansorge *et al.* 2000) and in all cases it has been shown that they are eddies. This area, to the leeward side of the South-West Indian Ridge was also used extensively by southern elephant seals *Mirounga leonina* tracked from Marion Island (Jonker & Bester 1998). Grey-headed albatrosses breeding on South Georgia have also been shown to forage at warm eddies in the PFZ which occur predictably due to bathymetric features (Rodhouse *et al.* 1996). It is worth noting that although many of the eddies occurring on the South West Indian Ridge, both cyclonic and anti-cyclonic, have been shown to eventually drift by the Prince Edward Islands (Ansorge & Lutjeharms. in press), the birds preferred to utilize recently formed eddies. This suggests that the biological content of these eddies may change with time and/or eddies located closer to the island experience higher levels of competition and local depletion by the large populations of non-aerial (therefore less mobile) predators (i.e. furseals and penguins) breeding on Marion Island.

There thus appears to be two areas of high variability within the foraging range of grey-headed albatrosses: 1) the STFZ to the north of the island, and 2) the area where the ACC crosses the South West Indian Ridge to the south west of the island. These

two areas are at a similar distance from the island, and positive and negative anomalies were present in these areas during both the incubation and chick-rearing stages (Figs. 5.2 and 5.3). It is thus unclear why birds would switch to foraging exclusively to the south of the island during chick-rearing. The most plausible explanation is that although the main area of variability to the southwest of the island occurs at *ca* 700-900 km from the island, eddies appear to persist closer to the island as well (Fig.5.4, Ansorge & Lutjeharms in press). Weimerskirch (1999) showed that shorter foraging trips for albatrosses were aimed primarily at meeting the energetic demands of the chick, while longer foraging trips resulted in the adult regaining its body condition. Foraging to the south of the island along the South West Indian Ridge gives the adults a choice of several warm and cold eddies at a range of distances from the island and state of degradation or local depletion by less mobile predators. The selected foraging area will be a compromise between the energetic needs of the chick and the body condition of the parent. During incubation birds are away from the island for far longer periods (Chapter 4) and are not under the constraint of needing to return to their breeding locality in order to feed a chick at regular intervals. This allows adults to forage farther from the island and be more selective about their foraging area.

General diet during chick rearing

Diet samples, taken from a larger sample of birds (n = 30) during the chick rearing period, revealed a predominance of species associated with the SAZ and PFZ, thus confirming that the adults were foraging exclusively to south of the island during this period. Little is known about the biology and distribution of the most frequently occurring fish species, *Magnisudis prionosa* (Gon & Heemstra 1990); although it has been recorded in the diets of grey-headed and black-browed albatrosses *Thalassarche melanophrys* at South Georgia (Reid *et al.* 1995), as well as several other sub-Antarctic species known to feed mainly in the PFZ, including king penguins *Aptenodytes patagonicus* (Hindell 1988), Antarctic fur seals *Arctocephalus gazella* and Subantarctic fur seals *Arctocephalus tropicalis* (Green *et al.* 1990, Klages & Bester 1998). Four of the six myctophids found in our samples (*E. antarctica, E. carlsbergi, G. bolini* and *K. andersoni*) only occur in the upper water column at, or south of, the APF (Gon & Heemstra 1990). To date little is known about the fish stocks in the SAZ and PFZ. A limited number of acoustic and trawling surveys

conducted in the Atlantic sector of the Southern Ocean indicate that during the austral summer high myctophid stocks are associated with the APF and southern parts of the PFZ (Filin *et al.* 1991, Pakhomov *et al.* 1994, 1996).

The most frequently-occurring fresh prey item, the ommastrephid squid *Martialia hyadesi*, is strongly associated with the APF (Rodhouse *et al.* 1992) and has also been found to associate with warm eddies that form at the APF in the Scotia Sea (Rodhouse *et al.* 1996). This species has major potential for commercial exploitation (Rodhouse *et al.* 1997). *M. hyadesi* is a major squid prey of the mollymawk albatrosses breeding across the entire Southern Ocean (Rodhouse *et al.* 1990, Ridoux 1994, Waugh *et al.* 1999). Knowledge of the environmental parameters that govern its abundance and distribution are therefore of utmost importance.

Prey items associated with particular oceanographic features

These data suggest that birds were feeding mostly on larger predators (e.g. the fish *Magnisudis prionosa* and the squid *Martialia hyadesi*) at the edges of anomalies, where they presumably are attracted by the presence of potential prey such as myctophids and crustaceans (e.g. decapod shrimps). These in turn could have been attracted by elevated stocks of copepods, amphipods (particularly *Themisto gaudichaudii*) and euphausiids, which were also well represented in the diet. Small amphipods (mainly *Themisto gaudichaudii*) and euphausiids are the most consistent components in the diet of adult Antarctic myctophids (Koslov & Tarverdieva 1989). Furthermore, amphipods were found in a stomach of an unidentified fish in one of the albatross diet samples. Although this is a single opportunistic record, it confirms the structure of the food chain suggested above. Continuous acoustic measurements in this region clearly indicated that the biomass of large plankton and micronekton (>20mm in length) was consistently elevated at both warm and cold eddies (Pakhomov & Froneman 2000). Although the acoustic data are blind, these findings provide first evidence that positive and negative anomalies (*sensu* warm and cold eddies) might have elevated stocks of potential prey for epipelagic fish and squid, which in turn are preyed upon by grey-headed albatrosses. Rodhouse *et al.* (1996) reported that grey-headed albatrosses tracked from South Georgia, while exploiting warm eddies at the PFZ, fed mainly on the squid *Martialia hyadesi*. Sampling in these areas using pelagic trawls revealed that these squid were feeding mainly on

myctophids, which presumably become concentrated by warm eddies. Myctophids, euphausiids and amphipods, especially *Themisto gaudichaudii*, are also the major prey items of the squid *Martialia hyadesi* at the APF in the Scotia Sea (Rodhouse *et al.* 1992). Rodhouse & White (1995) demonstrated that in the Scotia Sea the dominant predators in the epipelagic system at the PFZ were squid. My data suggest that a predatory fish, *Magnisudis prionosa,* may also be an important member of the epi-pelagic predator community at the PFZ in the Southern Indian Ocean.

Exactly how positive and negative anomalies (*sensu* warm and cold eddies) concentrate prey near the surface is unknown. However, Wiebe (1982) demonstrated that slope-water euphasiids move downwards in decaying cold eddies in an attempt to stay in their preferred environment. It is thus possible that crustaceans might be forced to move upwards in decaying warm eddies in order to stay in their preferred environment. This would make them accessible to epi-pelagic predators and trigger off a trophic chain ending with top predators breeding on the Prince Edward Islands. It has recently been demonstrated that eddies spawned off the major frontal systems are rich in zooplankton/micronekton standing stock (Wiebe & Youce 1992, Craddock *et al.* 1992, Pakhomov *et al.* 1994, Pakhomov & Perissinotto, 1997). The eddies may persist for as long as up to 6 months (Lutjeharms & Gordon 1987, Lutjeharms & Valentine 1988) and exhibit elevated primary productivity at the edges (Dower & Lucas 1993, Froneman *et al.* 1999). Therefore, eddies are regarded as an important vehicles in transporting unique or dense zooplankton communities providing ideal feeding grounds for top predators (Sugimoto & Tameishi 1992, Barange *et al.* 1998). However, physical mechanisms and trophic links within eddies are as yet poorly understood and will be the subject of future research in the region southwest of the Prince Edward Islands. The data presented in this paper, present the first insights into the nature and importance of these physical oceanographic features.

The findings of this study further demonstrate that productive eddies occurred at a range of distances from the island. Eddies that occur closer to the island could also be important for non-aerial predators breeding on Marion Island (i.e. penguins and seals). These species are not able to cover the vast distances covered by albatrosses, but are able to exploit resources occurring further down in the water column than albatrosses. Myctophids, which become concentrated at warm eddies (Rodhouse *et al.* 1996),

dominate the diets of both King Penguins and fur seals at Marion Island (Adams & Klages 1987, Klages & Bester 1998). Furthermore, king penguins tracked from nearby Crozet Island showed that breeding birds made long, directed foraging trips (indicative of a predictable food resource) to the PFZ (Jouventin *et al.* 1994). Finally, elephant seals tracked from Marion Island also showed intensive foraging activity on the leeward side of the South West Indian ridge. We therefore suggest that this 'hotspot' of eddies, created by the ACC crossing the Southwest Indian Ridge, could be an important component of the 'life-support system' for numerous globally significant populations of seabirds and seals breeding on Marion Island.

Conservation Implications

Grey-headed albatrosses, along with other species of albatrosses and petrels , are killed in significant numbers by pelagic tuna longline fishing vessels operating south of Africa (Ryan & Boix-Hinzen 1999). Chapter 4 showed a broad scale overlap between the foraging grounds of grey-headed albatrosses and the main pelagic longline fishing areas, south and south east of Africa. However, tuna are known to concentrate at highly productive mesoscale oceanographic features and as a consequence tuna longline fishing effort is often highly localized at these features (Uozumi *et al.* 1997). This study demonstrated that grey-headed albatrosses are also able to locate and target such productive mesoscale oceanographic features. This behaviour occurred both within a known longline fishing area (i.e. the STFZ) and in area where there were no fishing vessels (i.e. the PFZ). This behaviour could mean that the spatial interaction between albatrosses and tuna longline fishing effort at the STFZ is actually far more intense and occurs at a finer scale than previously expected. With the increasing utilization of modern technology, more vessels will have access to satellite imagery to aid them locate such productive oceanographic features. It is thus probable that the spatial overlap with albatross foraging areas will become even more intense in the future. Unless effective seabird mitigation measures (Brothers *et al.* 1999) are employed by these vessels, this interaction will lead to higher mortality rates in albatrosses.

Appendix 5.1 The relative abundance, frequency of occurrence and estimated lengths and masses of prey items identified in grey-headed albatross diet samples collected during the chick-rearing period at Marion Island, 1998.

	Relative abundance	Frequency of occurrence		Estimated length (mm)		Estimated Mass (g)	
		Total (%)	Fresh (%)	Mean ± SD	Range	Mean ± SD	Range
FISH	75	90	63				
Family Macrouridae	2	3	3				
Cynomacrurus piriei	1	3	3				
Unid. *Macrouridae*	1	3					
Family Myctophidae	14	27	10				
Electrona antarctica	4	3		103.8 ± 38.2	70.7-136.9	20.5 ± 18.2	4.7-36.2
Electrona carlsbergi	1	3		58.2		3.58	
Electrona subaspera	1	3	3	92.5		14.9	
Gymnoscopelus bolini	2	3					
Gymnoscopelus piabilis	1	3	3	167.9		99.9	
Gymnoscopelus sp.	1	3					
Krefftichthys andersoni	3	7		44.5 ± 2.4	41.7-45.9	0.878 ± 0.14	0.71-0.96
Unid. *Myctophidae*	1	3	3	52			
Family Paralepididae							
Magnisudis prionosa	39	30	20	452.5 ± 68.6	198.2-624.4	321.6 ± 48.7	140.9-443.7
Family Photichthydae							
Photichthys argenteus	2	7	7	309.5		126.3	
Unidentified Fish	18	53	33	324.4 ± 76.3	270-378		
SQUID	325	97	68				
Family Chiroteuthidae							
Chiroteuthis sp.	66	33	7	111.4 ± 10.7	82.3-150.8	36.1 ± 10.4	13.9-86.3
Family Cranchiidae							
Galiteuthis glacialis	65	30		219 ± 13.5	187.6-248.7	93.2 ± 14.3	62.9-126.6
Family Gonatidae							
Gonatus antarcticus	8	20		290.4 ± 12.1	270.6-304.9	178.6 ± 28.6	134.1-214.1
Family Histioteuthidae							
Histioteuthis eltaninae	14	33	3	62.2 ± 11.1	44.1-90.8	86.5 ± 31.0	44.8-175.7
Family Mastigoteuthidae							
Mastigoteuthis psychrophila	3	7		164.9 ± 41.4	117.4-193.0	203.3 ± 116.8	69.9-287.7
Family Neoteuthidae							
Alluroteuthis antarctica	14	30	3	147.1 ± 31.6	70.4-202.0	389.5 ± 210.5	38-898.9
Family Ommastrephidae							
Martialia hyadesi	46	47	27	233.3 ± 35.5	150-287.7	227.5 ± 105.9	60.9-445.6
Family Onychoteuthidae	61	60	10				
Konakovia longimana	47	53	10	387.8 ± 110.7	149.3-533.7	1 648 ± 957.3	87.5-3 556.1
Moroteuthis ingens	1	3		600.4		2 625.6	
Moroteuthis robsoni	3	7		309.1 ± 26.5	284.5-337.1	766.3 ± 104.0	671.8-877.6
Family Psychroteuthidae							
Psychroteuthis glacialis	1	3		26.2		90.9	
Unidentified Squid	47	43					
CRUSTACEANS	174	70	70				
Amphipoda	116	27	27				
Themisto guadichaudii	114	20	20				
Unidentified amphipods	2	7	7	29.5 ± 4.9	26-33		
Decapoda	18	40	40				
Austropandalus grayi	2	7	7	69.5 ± 7.8	64.0-75.0		
Pasiphaea scotia	10	23	23	33.3 ± 6.3	24.0-40.0		
Unidentified decapods	6	9	9				
Euphausiacea	36	17	17				
Euphausia superba	4	3	3				
Unidentified Euphausiid	32	13	13				
Isopoda							
Unidentified Isopods	4	13					
OTHER	10	20	7				
Goose barnacles	4	3	3				
Penguin feathers	3	10					
Jelly fish	2	7	7				
Mammal lung & stomach	1	3	3				

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CHAPTER 6

Population trends of albatrosses and petrels at sub-Antarctic Marion Island

ABSTRACT

Population changes are reported for five species of procellariiform seabirds breeding at Marion Island: wandering albatrosses *Diomedea exulans*, grey-headed albatrosses *Thalassarche chrysostoma*, northern giant petrels *Macronectes halli*, southern giant petrels *M. giganteus*, and white-chinned petrels *Procellaria aequinoctalis*. The four large surface nesting species (wandering and grey-headed albatrosses, and northern and southern giant petrels) show similar population trends over the last 16-18 years. All were stable or decreasing during the 1980s, followed by a recovery period during the early to mid-1990s. Recently all species have once again stabilized or decreased in numbers. The white-chinned petrel population appears to have suffered a large decrease during the late 1990s. Population trends of wandering albatrosses at Marion Island were strongly correlated with other Indian Ocean populations, but were different from the Atlantic Ocean population. These similarities within the southern Indian Ocean suggest a common cause and can be explained by changes in tuna *Thunnus* spp. longline fishing effort in the region. An increase in tuna longlining during the mid 1990s, as well as recent large scale Illegal, Unregulated and Unreported (IUU) longline fishing for Patagonian toothfish *Dissostichus eleginoides* close to Marion Island, could be contributing to the recent decreases in some of these species. Adoption of mitigation measures and an effective means of dealing with IUU longline fishing is necessary to reduce the impacts of longline fishing on populations of albatrosses and petrels.

INTRODUCTION

Many species of albatrosses and petrels have experienced global decreases in their population sizes during the past three decades (Gales 1998). Mortality associated with commercial longline fishing operations has been identified as the most important threat facing these populations (Gales 1993). Birds are killed when they attempt to snatch baited hooks being deployed at the stern of longline fishing vessels, and are subsequently drowned (Brothers 1991). Several types of longline fishing operations exist, which vary in their spatial distribution and technique (Brothers *et al.* 1999). Furthermore, the effort and spatial distribution of these fisheries have fluctuated over time (Polacheck & Tuck 1995). These variations result in differences in both the number and species of seabirds killed over space and time.

The largest longline fishery in the Southern Ocean, both in terms of fishing effort and spatial extent, is the pelagic fishery for tuna *Thunnus* spp. (Brothers *et al.* 1999). This fishery is mainly concentrated at the Sub-Tropical Front (STF) and is responsible for death of tens of thousands of albatrosses and petrels each year (Brothers 1991, Gales *et al.* 1998, Ryan & Boix-Hinzen 1998, Ryan *et al.* in press). The fishery started in the 1950s and has undergone large fluctuations in effort and spatial distribution over time (Polacheck & Tuck 1995, Tuck & Polacheck 1997). In the Southern Indian Ocean, this fishery initially increased quickly during the 1960s, before reaching plateau of *ca* 60 million hooks per annum during the 1970s (Fig. 6.1). The 1980s saw a further large increase in effort, and was consistently above 90 million hooks per year between 1983 and 1989. The early 1990s saw decreased effort, before increasing again to higher levels during the mid 1990s (Fig. 6.1). (Tuck & Bulman 2001). Whilst effort in the Indian Ocean has undergone large fluctuations over time, effort in the Atlantic Ocean has shown a more steady linear increase of 3.45% per annum since inception in the early 1960s (Tuck & Polacheck 1997; Fig. 6.1).

The late 1980s saw the development of another large longline fishing industry in the Southern Ocean, demersal longlining for Patagonian toothfish *Dissostichus eleginoides* (Brothers *et al.* 1999). This fishery is concentrated on the shelf areas surrounding the sub-Antarctic Islands and at sea mounts. Fishing commenced in the austral summer of 1985/86 around South Georgia, Atlantic Ocean (Dalziell & De

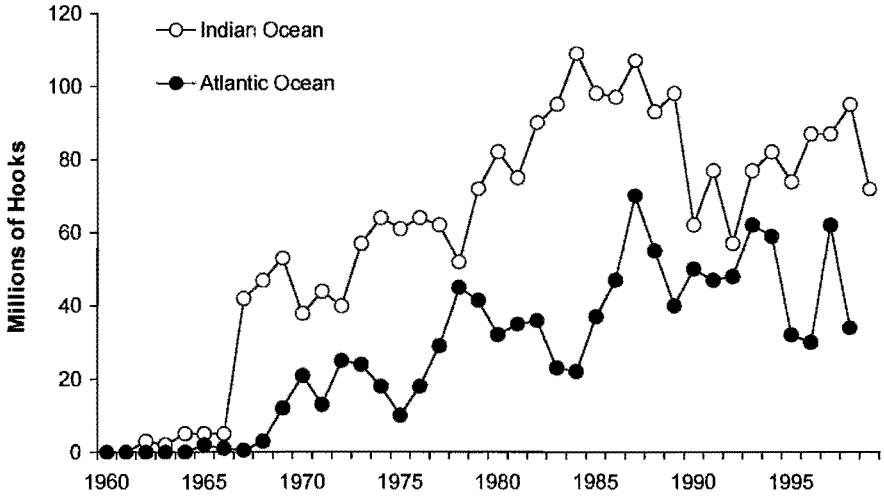

Figure 6.1. Pelagic longline fishing effort in the southern Indian (>30°S; 20°E – 141°E) and southern Atlantic (>30°S; 70°W – 20° E) Oceans (adapted from Tuck & Bulman 2001).

Poorter 1993), and was followed by fishing around Kerguelen, southern Indian Ocean, (Duhamel *et al.* 1997) in 1990. It was not until 1996 that sanctioned fishing started around the Prince Edward Islands after considerable poaching by IUU (Illegal, Unregulated and Unreported) vessels (Chapter 1). The overall seabird by-catch in the vicinity of Prince Edward Islands could have been between 8 500 and 18 500 birds in the four years, 1996–2000 (Chapter 1). This was largely due to large numbers of IUU fishing vessels, which were unlikely to be using effective seabird mitigation measures. As the vast majority of birds were breeding adult males the impact on the population was greater than if all age classes and sexes were killed (Chapter 1). The mid 1990s saw the start of longlining for hake *Merluccius* spp. off the coast of South Africa. This industry is estimated to kill *ca* 8000 white-chinned petrels annually (Barnes *et al.* 1997).

It is therefore clear that seabirds breeding at various localities in the Southern Ocean have been subject to fluctuating pressures from longline fishing. In this Chapter, I report on population trends of seabirds on Marion Island (Prince Edward Islands) in relation to temporal and spatial changes in longline fishing in the southern Indian Ocean. I also compare trends on Marion to those at other breeding localities in the Southern Ocean, in an attempt to assess the possibility of common underlying causes.

METHODS

Ornithological field assistants on Marion Island (46°54'S, 37°45'E) conducted standardized annual counts of incubating birds of five seabird species, which are killed in significant numbers by longline fishing operations in the southern Indian Ocean: wandering albatross *Diomedea exulans*, grey-headed albatross *Thalassarche chrysostoma*, northern giant petrel *Macronectes halli*, southern giant petrel *Macronectes giganteus*, and white-chinned petrel *Procellaria aequinoctialis*. All the counts from the mid 1980s were conducted shortly after egg laying was complete. Whole island counts were made for the four surface nesting species: wandering and grey-headed albatrosses, and northern and southern giant petrels. Active white-chinned petrel burrows were counted within an easily defined area (*ca* 15 ha) adjacent to the base station. White-chinned petrel burrows were classified as active if any sign of activity was noted i.e. vegetation cropped at entrance, signs of digging of claw marks, faeces, or vocal response to a tape-recorded call. In general active burrows are easily discerned at the time of the count (1st week of December -immediately after the peak of egg-laying) as all active burrows are newly renovated.

For wandering albatrosses standardized annual counts of incubating birds have been conducted since the austral summer of 1987/88. For six years prior to this, numbers of brooded chicks were counted. I used breeding success data from long term study colonies (*ca* 200 nests) to adjust these data to estimate the number of incubating birds. Although these adjusted data are presented, they are denoted differently from the actual counts of incubating adults. Two counts during the 1970s also exist for this species. The actual dates at which these counts were conducted are not known. However, because there are two counts over a three year period during the 1970s and wandering albatrosses are relatively easy to count on Marion Island (they are large and conspicuous and breed on open plains), I have presented these counts. However, these counts should be treated with more caution than the rest of the data set.

For three other three surface-nesting species (grey-headed albatross, northern giant petrel, and southern giant petrel) accurate annual counts were conducted in >75% of the years since the austral summer of 1984/85. Although estimates of grey-headed

average of the two counts in 1970s ($t = 3.36$; $p = 0.0084$). The average of all counts in the 1990s was 23% higher than the average of all counts in the 1980s ($t = 4.53$; $p = 0.0003$).

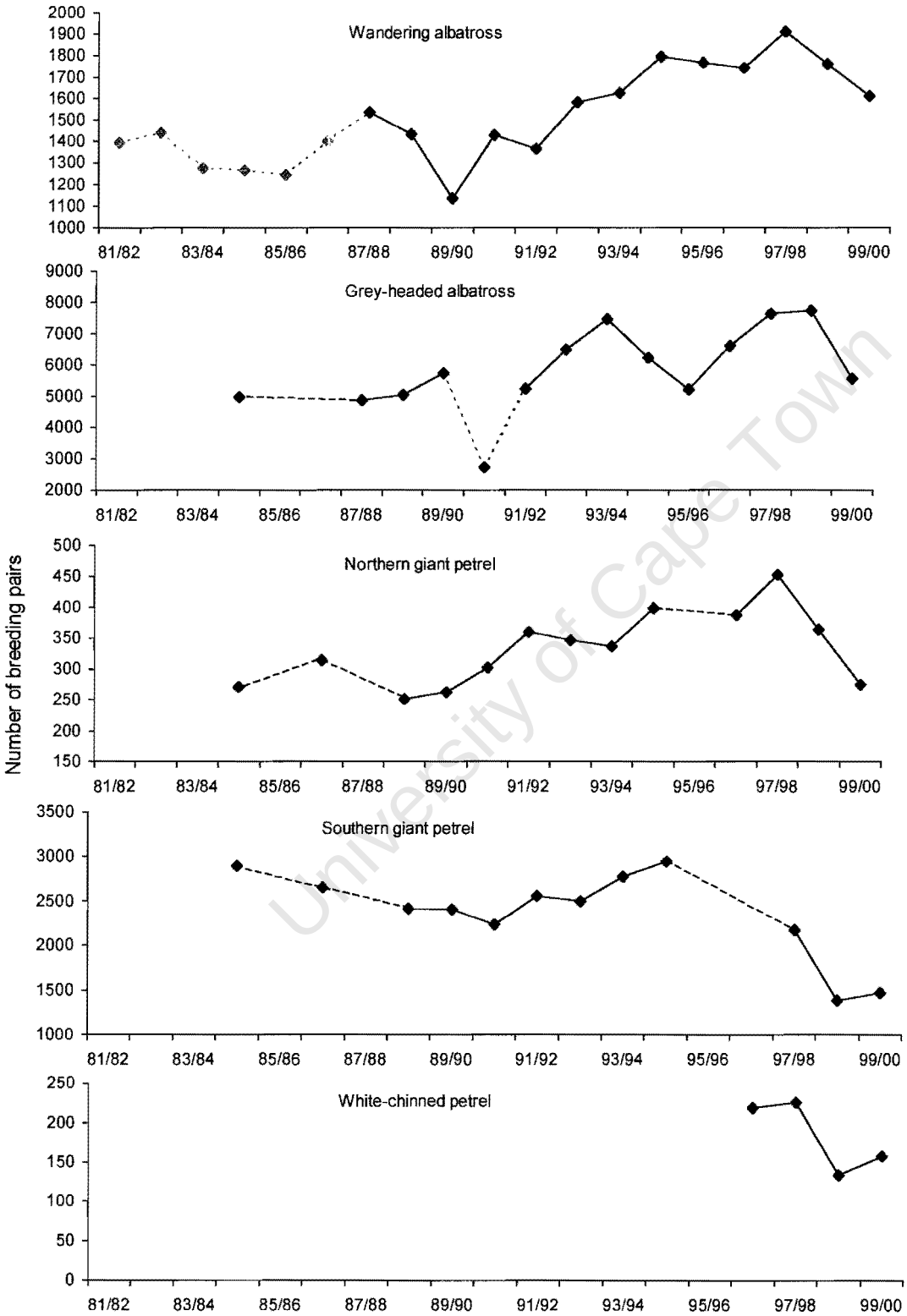

Figure 6.2 Population trends of five species of procellariiforms breeding on Marion Island, since the 1980s. Dashed lines indicate uncertainty about trends due to missing or less reliable data points.

Table 6.1 Annual rates of population change (%) of albatrosses and petrels breeding on Marion Island, as given by a linear regression over the given time period.

Species	1980s to Early 1990s	Early to Late 1990s	Late 1990s
Wandering albatross	- 1.5	+ 5.5	- 8.2
Years	*1974/75-1989/90*	*1989/90-1997/98*	*1997/98-1999/2000*
No. of data points	*11*	*9*	*3*
p	*0.048*	*<0.01*	*<0.01*
Grey-headed albatross	- 1.8	+ 3.6	*
Years	*1984/85-1991/92*	*1991/92-1998/99*	
No. of data points	*6*	*8*	
p	*0.70*	*0.14*	
Northern giant petrel	- 1.9	+ 5.6	- 11.3
Years	*1984/85-1989/90*	*1989/90-1997/98*	*1997/98-1999/2000*
No. of data points	*4*	*8*	*3*
p	*0.58*	*<0.01*	*<0.01*
Southern giant petrel	- 4.0	+ 6.5	- 14.6
Years	*1984/85-1990/91*	*1990/91-1994/95*	*1994/95-1999/2000*
No. of data points	*5*	*5*	*4*
P	*<0.01*	*0.012*	*0.042*
White-chinned petrel			- 14.1
Years			*1996/97-1999/2000*
No. of data points			*4*
P			*0.21*

Grey-headed albatross

This species displayed a greater annual fluctuation in numbers of breeders than the other species, making it more difficult to detect long term trends (Table 6.1, Fig. 6.2). The population appears to have decreased between the mid 1980s and 1990/91, but this is driven largely by a very low count in 1990/91. This count was 52% lower than the previous year and the count of fledglings for this breeding season yielded a breeding success of 77% (20% higher than the next highest breeding success recorded in 12 years). This suggests an undercount of incubating birds. We therefore conclude that the population was stable and possibly decreasing over this period. Between 1990/91 and 1998/99 the population increased at +7.3% pa. However, this large increase is once again largely driven by the low count in 1990/91. If we remove the 1990 count the average population increase over this period is +3.6% pa. The average of all counts in the 1990s (n = 9) was significantly higher than all counts done in the 1980s (n = 5) (t = 3.08; p = 0.0096), giving us confidence than the population increased (or recovered) during the 1990s. The 1999/00 count showed a 28% decrease, the largest annual decrease since the exceptionally low 1990 count.

albatross and northern giant petrel populations were made in 1974/75 (Williams *et al.* 1979) these counts were intended as rough population estimates and not intended for use in the analysis of population trends. I have not considered these data points in this analysis for the following reasons: 1) no record exists of the exact date during the breeding season at which these counts were conducted, and 2) interpreting single counts of breeders per decade for a long-lived species (and especially biennially breeding species) is hazardous.

Average annual rate of population change was calculated as discrete geometric growth, using the equation $N_t = N_0 \lambda^t$ (where N_t = the population at year t; N_0 = the population at year 0, λ = discrete annual growth rate, t = number of years). Although environmental and demographic factors may cause inter-annual variation in the proportion of the overall population that attempts to breed each year (Weimerskirch 1998, Chapter 7), consecutive counts of breeding birds over several years is still the most widely used indicator of population trends of albatrosses and petrels (e.g. Gales 1998). Annual variability of populations was obtained by calculating the residuals of the smoothed data. Data were smoothed using the weighted average of the nearest nine neighbours (Savitzky & Golay 1964). The El Niño-Southern Oscillation (ENSO) index NINO 3 was used as an indicator of environmental variability. This index is the sea surface temperature anomaly averaged over 5°S, 5°N and 150°W, 90°W (i.e. the eastern equatorial Pacific). NINO3 data was obtained from the International Research Institute for Climate Prediction (http:/ingrid.ldgo.columbia.edu/SOURCES/Indices./ensomonitor).

RESULTS

Wandering albatross

Numbers of wandering albatrosses breeding at Marion Island decreased steadily from the mid 1970s until the late 1980s at a rate of –1.5% per annum (pa), before again increasing though the 1990s at a rate of +5.5% pa. The final two years of the nineties once again saw a substantial decrease at –8.2 % pa (Figs. 6.2 & 6.3, Table 6.1). If the two counts in the 1970s are ignored, the population decreased at a rate of –0.5% pa during the 1980s. The average of all counts in the 1980s was 21% lower than the

Northern giant petrel

The number of northern giant petrels breeding at Marion Island decreased from the mid 1980s to 1989/90 at a rate of –1.86% pa (Table 6.1, Fig. 6.2). However, counts fluctuated substantially over this period decreasing our confidence in this trend. Between 1989/90 and 1997/98 the population increased at a rate of 5.6% pa. The final two years of the 1990s saw a dramatic decrease at –11.3% pa.

Southern giant petrel

Number of southern giant petrels decreased at a rate -4.0% pa from the mid 1980s to 1990/91 and then increased at +6.5% pa from 1990/91 until 1994/95 (Table 6.1, Fig 6.2). There were no counts between 1994/95 and 1997/98 but the population in 1997/98 was 26% lower than 1994/95. This decrease continued in subsequent years. If we assume that the decrease started in 1994/95, the rate of decrease over the second half of the 1990s was –14.6% pa.

White-chinned petrels

This species has only been monitored for the four seasons commencing 1996/97, during which time the population has decreased by 34% at an annual rate of 14.1% (Table 6.1, Fig. 6.2). The main decrease took place between 1997/98 and 1998/99.

Annual variability

Annual variability in wandering albatross and northern giant petrel numbers was positively correlated with annual maximum ENSO index (Table 6.2). These correlations were mainly driven by the two ENSO events during the study period: The large event of 1997/98 and a smaller event during 1986/87. Grey-headed albatrosses also showed some indication of a similar correlation, although the correlation was not significant. The best correlation was found without any lag period.

Table 6.2 Correlation coefficients of annual maximum ENSO indices (NINO 3), with the residuals of smoothed counts of albatrosses and petrels breeding at Marion Island.

Species	*n*	*r*	*P*
Wandering albatross	18	0.579	0.012
Grey-headed albatross	14	0.4059	0.15
Northern giant petrel	14	0.6251	0.017
Southern giant petrel	13	-0.176	0.565

DISCUSSION

Comparison between species

Wandering albatrosses and grey-headed albatrosses are both biennial breeders and are thus prone to larger fluctuations in breeding population size in successive years. The other three species breed annually. Despite these differences, the four species for which long term data (>10 years) are available (wandering albatross, grey-headed albatross, northern giant petrel and southern giant petrel) all showed similar long term populations trends over the study period (Table 6.1, Fig. 6.2). Populations were either stable or decreasing during the 1980s, followed by an increase during the early and mid 1990s. The late 1990s has seen the populations stabilizing and possibly decreasing. Although it is too early to assess whether the recent decreases are part of a long term trend, these were the largest decreases observed in the last decade, bringing populations back to levels last observed in the late 1980s. For southern giant petrels the current population size is in fact well below that of the late 1980s. Although only four years of data are available for white-chinned petrels, this species also appears to have suffered a recent decrease.

Interestingly, the highest counts of four of the five study species corresponded with 1997/98 El Niño event. Two of the study species (wandering albatrosses and northern giant petrels) also showed inter-annual variability that correlated with maximum annual ENSO indices. Surprising, the correlation was best without any lag period. Whether there is a causal relationship and if so the possible mechanism behind such a link, is unknown. However, White & Peterson (1996) described the presence of an Antarctic circumpolar wave of sea level pressure, sea surface temperature and wind stress that appeared to be linked to El Niño activity (although the mechanism is still unknown). Such variations in the environmental conditions in the Southern Ocean could affect these birds' ability to attain breeding conditions, thereby affecting inter-annual variations in numbers attempting to breed. However, El Niño effects are event-driven phenomena (e.g. Hays 1986) and although they are likely to affect inter-annual variability, it seems unlikely that they will affect underlying long-term population trends over several years.

The similarity in underlying long-term population trends of our study species suggests a common underlying cause that has a more sustained effect on the population. All the species analyzed are killed in significant numbers by pelagic tuna longline fishing vessels, which concentrate their efforts at the Sub-tropical Front or other productive oceanographic features (Ryan & Boix-Hinzen 1998). The Sub-tropical Frontal Zone also supports some of the highest densities of procellariiforms in the Southern Indian Ocean (Pakhomov & McQuaid 1996). Fluctuations in pelagic tuna longline fishing effort in the southern Indian Ocean can explain the overall long term population trends observed in large procellariiforms breeding on Marion Island. Fishing effort for tuna in the southern Indian Ocean increased greatly during the early 1980s, peaking during the mid 1980s (Fig. 6.1). This corresponds to a low point in procellariiform numbers on Marion Island during the mid to late 1980s. This was followed by a period of decreasing tuna fishing effort to the lowest point in two decades, in 1990. This period of decreasing effort corresponds with a period of recovery of procellariiform numbers on Marion Island during the early and mid 1990s. During the mid 1990s tuna longline fishing effort in the southern Indian Ocean increased again (Fig. 6.1), which could have contributed towards the recent decreases in populations of longline-affected species on Marion Island. However, with the exception of wandering albatrosses, all the species studied were also killed in significant numbers by the recently initiated demersal longline fishery for Patagonian toothfish, in the close vicinity of Marion Island (Chapter 1). This fishery could thus also have contributed to recent population trends, especially given the predominance of adult breeding birds killed.

Comparisons with other breeding localities

Population trends for Marion Island wandering albatrosses over the past 26 years were very similar to those of wandering albatross (and the closely related Amsterdam albatross *Diomedea amsterdamensis*) populations breeding at other Indian Ocean Islands (Weimerskirch *et al.* 1997) (Fig. 6.3, Table 6.3). These in turn, differed from the population trend of wandering albatrosses breeding at South Georgia in the South Atlantic Ocean (Fig 6.3, Table 6.2), which has shown a consistent decrease at a rate of –0.8% pa since the early 1960s (Croxall *et al.* 1998). Mortality due to longline fishing has been implicated as the main force driving population trends at other Indian Ocean Islands (Weimerskirch *et al.* 1997) and at South Georgia (Croxall *et al.* 1998). The

Table 6.3 The correlation coefficients (r) of counts of wandering albatross and closely related Amsterdam albatross populations breeding on three southern Indian Ocean islands (Marion, Possession and Amsterdam) and one South Atlantic Ocean island (South Georgia).

	Marion *p*	Possession *p*	Amsterdam *p*
Possesion *	0.67 *<0.01*		
Amsterdam *	0.78 *<0.001*	0.803 *<0.001*	
South Georgia **	0.21 *0.425*	-0.3185 *0.197*	-0.3177 *0.268*

* From Weimerskirch et al. (1997)
** From Croxall et al. (1998)

similarity of trends at Marion Island with other Indian Ocean populations, strongly suggests the same underlying cause. Weimerskirch *et al.* (1997) suggested that changes in total longline fishing effort in the Indian Ocean as well as changes in the spatial distribution of effort within the Indian Ocean, were the main driving force behind the population changes at other Indian Ocean populations. Differences in tuna longline fishing effort in the Indian and Atlantic oceans appear to be able to explain a large part of the difference in long term trends between the Indian Ocean and Atlantic Ocean populations. The Indian Ocean populations appear to have fluctuated according to changes in tuna longline fishing effort in the southern Indian Ocean (see discussion in previous section; Figs 6.1 & 6.3), whilst the Atlantic Ocean population has suffered a steady decrease over the last 30 years, which is concurrent with a steady increase in tuna longline fishing effort in this ocean (Figs 6.1 & 6.3). However, wandering albatrosses from South Georgia (Atlantic Ocean) also spend a substantial amount of their time at the edge of the Patagonian shelf (Prince *et al.* 1998) and thus come into contact with a increasing number of longline fisheries (Schiavini *et al.* 1998, Stagi *et al.* 1998). Whilst the similarity the Amsterdam albatross population trends with Wandering albatross trends in the rest of the Indian Ocean is intriguing, it should be noted that several land based conservation initiatives have led to more favourable breeding conditions here (BirdLife International 2000).

The recently-initiated longline fishery for Patagonian toothfish close to Marion Island does not appear to have adversely affected the population of wandering albatrosses. Only one wandering albatross fatality has been recorded by sanctioned vessels, with

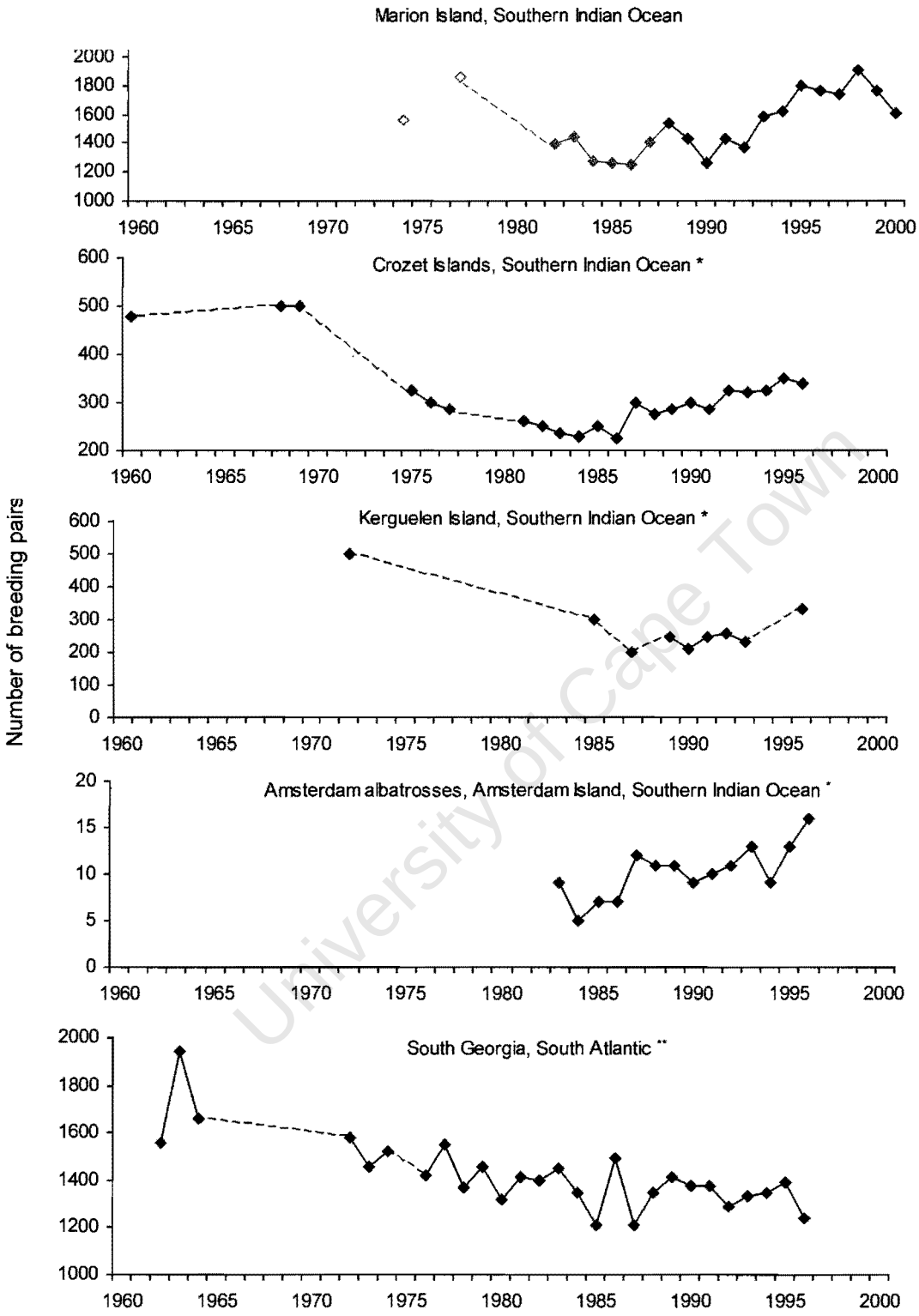

Figure 6.3 Trends of wandering albatross and the closely related Amsterdam albatross populations in the southern Indian and South Atlantic Oceans. * From Weimerskirch *et al.* 1997, ** from Croxall *et al.* 1998.

close to 100% observer coverage (Chapter 1). In fact during the early chick-rearing stage breeding wandering albatrosses obtained substantial amounts of food from scavenging around toothfish vessels (Chapter 3). However, the full benefits of this large source of supplementary food may have been offset by the negative effects of the large amounts of fishing debris (ropes, hooks and fishing lines) that was fed to the chicks (Chapters 2 & 3).

The high inter-annual variability recorded in counts of grey-headed albatrosses at Marion Island is similar to that recorded for this species at South Georgia (Croxall *et al.* 1998), making analysis of long term trends more difficult. However, it appears that this population experienced a population increase (or recovery) during the 1990s, after being stable during the 1980s. This is once again in contrast to the Atlantic Ocean population on South Georgia, which has experienced a linear decrease of –1.9% pa since 1976 (Croxall *et al.* 1998). The decrease on South Georgia has been linked to incidental mortality caused by longline fishing (Croxall *et al.* 1998). Grey-headed albatrosses show a strong association with oceanographic frontal systems (Chapter 5, Rodhouse *et al.* 1996) which are also prime areas for tuna longlining (Robertson 1998). Grey-headed albatrosses are consequently caught in significant numbers in tuna fisheries south of Africa (Ryan & Boix-Hinzen 1998) and around Australia (Gales *et al.* 1998) and New Zealand (Murray *et al.* 1993). Significant numbers of grey-headed albatrosses were also killed during the first year of longline fishing for patagonian toothfish in the close vicinity of Marion Island (Chapter 1) and probably continue to be killed by illegal fishing operators in these waters. Because of the large interannual variation it is not possible to determine whether the recent large decline in the Marion population is part of a long term trend. However the combined effect of increases in tuna effort in the mid 1990s (Tuck & Bulman 2001) as well as the initiation of a toothfish longlining industry close to Marion Island (and the problems associated with high levels of IUU fishing) has almost certainly led to an increased pressure on this species.

The increase in the breeding population of northern giant petrels observed on Marion Island between 1989/90 and late 1997/98 appears to be part of a global increase of this species over this period (Patterson *et al.* in press), which has been linked to a global increase in Antarctic *Arctocephalus gazella* and sub-Antarctic *A. tropicalis* fur seal

populations (Boyd 1993, Hofmeyr *et al.* 1997, Patterson *et al.* in press). Male northern giant petrels scavenge on seal carrion at a critical time during the early chick rearing period (Hunter & Brooke 1992, González-Solís *et al.* 2000). The sub-Antarctic fur seal population on Marion Island increased more than eight fold between 1975 and 1995 (Hofmeyr *et al.* 1997). This, along with a decrease in tuna longline fishing effort in the Indian Ocean, could thus have contributed to the observed increase in numbers of breeders at Marion Island during the early 1990s. More recently, during the late 1990s, the population has stabilized and possibly started decreasing. Increased pressure due an increase in tuna longlining effort in the mid 1990s (Tuck & Bulman 2001) as well as the recent initiation of longline fishing for Patagonian toothfish in the close vicinity of Marion Island (Chapter 1) could be contributing towards increased pressure on this species. During the first four years of longline fishing for toothfish around Marion Island (1996/97) it is estimated that between 100 and 200 northern giant petrels were killed (mainly by unsanctioned vessels) (Chapter 1). Most of these birds were breeding adults (*ca* 7-16% of the breeding population) (Chapter 1).

Globally, southern giant petrels appear to have declined between the mid 1980s and the late 1990s (Patterson *et al.* in press). Overall, the population on Marion Island also followed this trend, but during the early to mid 1990s the Marion population increased and only started declining again rapidly in late 1990s. Population decreases of southern giant petrels elsewhere, particularly in the close vicinity of research stations on the Antarctic Peninsula, have been partly attributed to increases in human disturbance (e.g. Croxall *et al.* 1984, Woehler *et al.* 1990). Southern giant petrel colonies located closest to the research station on Marion island have almost completely disappeared between 1993 and 1998 (pers. obs.). The late 1980s and early 1990s saw the implementation of an intense cat eradication program on Marion Island (Bester and Skinner 1991) which could have led to increased human disturbance. However, the population actually increased during this period and the subsequent decrease (during the late 1990s) has occurred at such a rapid rate (i.e. *ca* 50% decline in 4 years) that it can only be explained by a decrease in the proportion of adults breeding, decreased adult survival or increased emigration rates. Southern giant petrels are killed in significant numbers in both pelagic tuna longline operations (Gales *et al.* 1998) as well as demersal longline fishing for Patagonian toothfish, in the close vicinity of Marion Island (Chapter 1). The recent increase in tuna longline

fishing effort as well as the development of a toothfish longline fishery close to the island could thus be major contributors to this recent decline.

Population sizes and trends of white-chinned petrel populations at other locations are not well documented. However, the decrease recorded on Marion Island appears to be part of a global decline, associated with widespread mortality in longline fisheries. An overall decrease of 28% was recorded between 1981 and 1998 on South Georgia, South Atlantic (Berrow *et al.* 2000). White-chinned petrels are one of the widest-ranging seabirds when breeding (Weimerskirch *et al.* 1999) and are also able to dive to depths of over 10 metres (Huin 1994), making them extremely vulnerable to a wide range of longline fishing operations. White-chinned petrels are caught in significant numbers in almost all longline fisheries operating in the Indian Ocean, from demersal fisheries operating in continental waters (Barnes *et al.* 1997), pelagic tuna fisheries operating on the highs seas (Ryan & Boix-Hinzen 1998), to demersal toothfish fisheries operating in the close vicinity of their breeding islands (Chapter 1). During the period 1996-2000, it was estimated that between 7000 and 14000 white-chinned petrels were killed by toothfish longline operations around Marion Island (Chapter 1). This was mostly due to a large fleet of illegal vessels. Most of these birds were breeding males (Chapter 1). It is thus not surprising that local and global decreases in numbers of this species are being observed.

CONCLUSION

Changes in the breeding population sizes of the four large, surface-nesting procellariiforms for which there are long term data, show similar long term trends. Populations were all stable or decreasing during the 1980s, increasing during the early to mid 1990s, and appear to stabilize or decrease again during the late 1990s. These trends are also similar to those experienced by wandering albatross populations breeding at other Indian Ocean Islands, suggesting a common underlying cause. These population trends reflect changes in tuna longline fishing effort in the southern Indian Ocean, which was at its highest during the mid 1980s, declining to its lowest point in three decades in 1990, then increasing again during the mid to late 1990s. The recent increase in tuna longline fishing effort as well as the development of a demersal longline fishery for Patagonian toothfish close to Marion Island (and the associated

problems with high levels of IUU fishing), could result in increased pressure on these populations. The adoption of mitigation measures as proposed by Brothers *et al.* (1999) by all longline fishing vessels, as well as effective means of curbing large-scale IUU longline fishing, are required to decrease the impact of longline fishing on these populations.

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CHAPTER 7

Population dynamics of wandering albatrosses *Diomedea exulans* breeding at sub-Antarctic Marion Island

ABSTRACT

The Prince Edward Islands support the largest breeding population of the vulnerable wandering albatross *Diomedea exulans* in the world. The number of birds breeding in this population has fluctuated over the past three decades. This chapter describes the changes in several demographic parameters that appear to be influenced by both environmental and anthropogenic effects. The proportion of first-time breeders in the population was positively correlated with the maximum ENSO index, while the annual survival rates of adults and juveniles was negatively correlated with Japanese pelagic longline fishing effort in the Southern Indian Ocean. Adult survival rates were significantly correlated with those recorded on neighbouring Possesion Island (Crozet Islands). The average survival rate of adult females was lower than males. Males who lost partners took longer than females to find a new mate, suggesting a male-biased population. Survival rates of juvenile males and females did not differ. The age distribution of first time breeders has progressively shifted towards younger birds during the 1990s. Higher than expected survival rates of breeding adults during the late 1990s may be linked to large amounts of supplementary food being made available by the initiation of a longline fishery for Patagonian Toothfish close to the islands during this time. Overall, breeding success was better than recorded at other localities, indicating that breeding conditions at Marion Island were relatively favorable. The implementation of international conservation initiatives to reduce the impact of longline fishing on this species and improve its conservation status, is recommended.

INTRODUCTION

The wandering albatross *Diomedea exulans* is currently classified as Vulnerable on the basis of population reductions in excess of 20% over most of its range within the last three generations (BirdLife International 2000). The main cause of this population decrease has been identified as mortality associated with long-line fishing operations (Gales 1998). The Prince Edward Islands are the most important breeding site for wandering albatrosses, hosting some 36% of the global population (Gales 1998). Information on the population dynamics of this population is thus of great importance for the conservation of this species.

Wandering albatrosses are highly efficient flyers (Weimerskirch *et al.* 2000) that are able to move vast distances from their breeding islands. Tracking studies (Chapter 3) as well as ring recoveries (Gales *et al.* 1998) indicate that wandering albatrosses breeding on Marion Island interact with a range of long-line fisheries occurring close to their breeding site, on the high seas, as well as in continental waters surrounding southern Africa and Australia. Of particular concern for the birds breeding on Marion Island is the time that tracked birds (particularly females) spent in the region of the Sub-tropical Front south of Africa (Chapter 3). This area is utilized intensively by pelagic longline fishing vessels targeting tuna *Thunnus* spp. (Tuck & Bulman 2001). Wandering albatrosses are particularly vulnerable to being killed by pelagic longlines (Brothers 1991, Gales *et al.* 1998, Ryan & Boix-Hinzen 1998) as these lines are only lightly weighted and sink slowly, thereby allowing the large and shallow diving wandering albatrosses to access the baited hooks (Brothers *et al.* 1999). In contrast wandering albatrosses were seldom killed in the demersal longline fishery for Patagonian toothfish *Dissostichus eleginoides* around Marion Island (Chapter 1). However, they did appear to obtain a substantial amount of the food that they fed their chicks from scavenging offal disposed by these vessels (Chapter 2 & 3).

Long term demographic studies of wandering albatrosses (and the closely related Amsterdam albatross *Diomedea amsterdamensis*) in the Indian Ocean show strong evidence that spatio-temporal changes in pelagic tuna long-line fishing effort in the Southern Indian Ocean may be the primary driving force behind the observed population changes (de la Mare & Kerry 1994, Weimerskirch *et al.* 1997). This

Chapter describes long term changes in population parameters at Marion Island in relation to possible anthropogenic and environmental influences.

METHODS

Long-term study colonies

All studies were conducted in three separate colonies located on the north-eastern coast of Marion Island (46°54'S, 37°45'E). Two of these study colonies have been monitored continuously since 1984, while the third was established in 1987. However, birds have been ringed opportunistically in these study colonies since 1976 (Appendix 1).

On average *ca* 230 pairs breed in the three study colonies each year (*ca* 14% of the Marion Island breeding population). Since their establishment, all fledgling chicks and adults breeding within these colonies have been banded with metal identification bands. Breeding birds also received unique colour alpha-numeric bands for quick identification and reduced disturbance. Nests are marked with numbered stakes once an egg has been noted at the nest. Both adults are then checked for metal and colour identification bands, and chicks are banded at five months after hatching. Nests were checked at weekly intervals from egg-laying until the completion of the brood/guard phase (*ca* two months after hatching). After this, the fate of nests was followed by means of monthly checks.

Once a year during peak incubation, every incubating bird on Marion Island (i.e. half of the annual breeding population) was checked for identification bands. For three seasons (1992, 1993, 1994) both mates in all the areas surrounding the study colonies were checked for bands and banded if not already banded. These studies were conducted in order to determine the level of migration out of the study colonies.

Survival data analysis

Encounter history matrices, which are required for capture-mark-recapture (CMR) analysis, were constructed from the resight data, treating multiple sightings in a year as a single sighting. Two matrices were constructed: the first included the sightings of

all known-age birds (i.e. birds ringed as chicks) in the monitoring colonies; the second included all adult birds that had been recorded breeding at least once in the colonies. Birds were assumed to age by one year at the beginning of January, which is the peak laying month on Marion Island (Percy FitzPatrick Institute. unpubl. data). The software program MARK (G. White, University of Colorado, U.S.A.), was used to obtain likelihood estimates of survival and capture probability parameters using primarily the Cormack-Jolly-Seber (CJS) model (Cormack 1964; Jolly 1965; Seber 1965). As it was impossible to distinguish mortality from permanent emigration in our study colonies, I refer to apparent rather than absolute survival. However, no bird that was recorded breeding within a study colony was recorded breeding elsewhere afterwards. I therefore believe that the effect of permanent emigration will be negligible.

The two fundamental parameters in these models are:

Φ = the survival probability for all animals between the ith and (i+1)th sample (i=1,2..., k-1),

p = the capture probability for all animals in the ith sample (i=1, 2..., k).

A Goodness of Fit (GOF) test (Appendix 2) suggested that there was underlying heterogeneity in the recapture probabilities. Estimates produced by CJS models can be biased for biennial breeding birds (Rothery & Prince 1990), because very few birds that breed successfully in a particular year will attempt to breed the following year. This behaviour introduces heterogeneity into the probability of recapture and leads to a bias in estimates. However, departures from the CJS model in general do not affect point estimates of survival (Carothers 1979), although it causes underestimation of standard errors of survival estimates (Burnham *et al.* 1987). Rothery & Prince (1990) analysed the problem by simulating data using a model of biennual breeders and showed that the bias was most marked in the first and last two years of the series. Accordingly, these estimates at the ends of the series were ignored for analysis of annual variation.

Evaluation of the relative fit of the models was accomplished using the Akaike Information Criterion (AIC) (Anderson *et al.* 1994) (Appendix 3). AIC is a standard procedure for model selection in a CMR context, and it weighs the quality of fit (deviance) and the precision (via the number of parameters), so as to select the most

parsimonious model that adequately describes the data (Lebreton *et al.* 1993; Anderson *et al.* 1994). It was used to select between the full time-, age- and sex-dependent model and various models assuming no differences in survival and capture probability between the sexes, between different-aged birds (for the combined cohort data), and between years. The likelihood ratio test, which provides a means to test between two nested models, was used to test the null hypothesis that the survival rates were constant between sexes, versus the alternative hypothesis that the survival rates varied between the sexes.

Fishery and environmental parameters

Longline fishing effort in the Southern Ocean was taken from Tuck & Bulman (2001). The El Niño-Southern Oscillation (ENSO) index NINO 3 was used as an indicator of environmental variability. This index is the sea surface temperature anomaly averaged over 5°S, 5°N and 150°W, 90°W (i.e. the eastern equatorial Pacific). NINO 3 data were obtained from the International Research Institute for Climate Prediction website (http:/ingrid.ldgo.columbia.edu/SOURCES/.Indices./ensomonitor).

RESULTS

Population trends and breeding success

Although only two whole island counts of were conducted during the 1970s, it appears that the breeding population was considerably higher than during the 1980s (Fig. 7.1). During the 1980s the population remained relatively constant, before increasing during the early to mid 1990s at a rate of *ca* 5% per annum (Chapter 6). During the late 1990s it appears as if the population has once again stabilised or started to decrease. Counts of birds breeding in the long term study colonies show similar trends to the whole island, although there is some interannual variation.

The overall breeding success in study colonies was 74.6 ± 4.2% (n = 17 seasons) and appeared to decrease from 1984 to 1996 (Fig. 7.2, $r^2 = 0.435$; $P = 0.014$). Since 1996, breeding success appears to have stabilized. Breeding success also varied with age (Fig. 7.3). Breeding success of birds younger than 10 years (63%) was significantly lower than birds between 10-25 years (76%) ($\chi^2 = 28.8$; $P < 0.001$). Breeding success

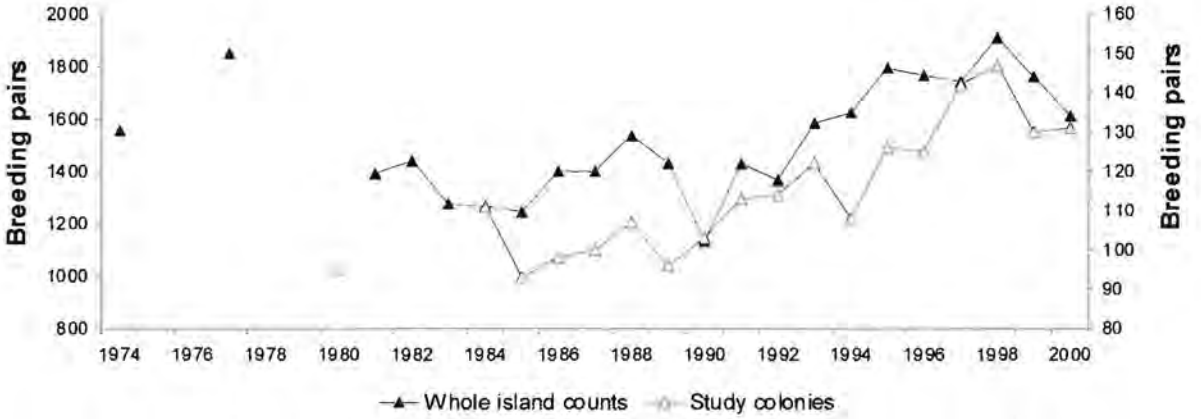

Figure 7.1 Counts of breeding pairs of wandering albatrosses on Marion Island and within the two long-term study colonies that have been monitored the longest.

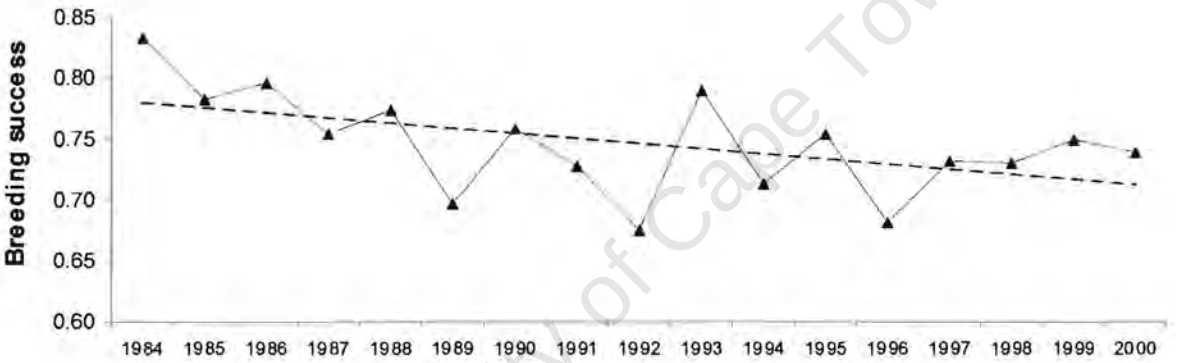

Figure 7.2 Breeding success of wandering albatrosses in long-term study colonies on Marion Island.

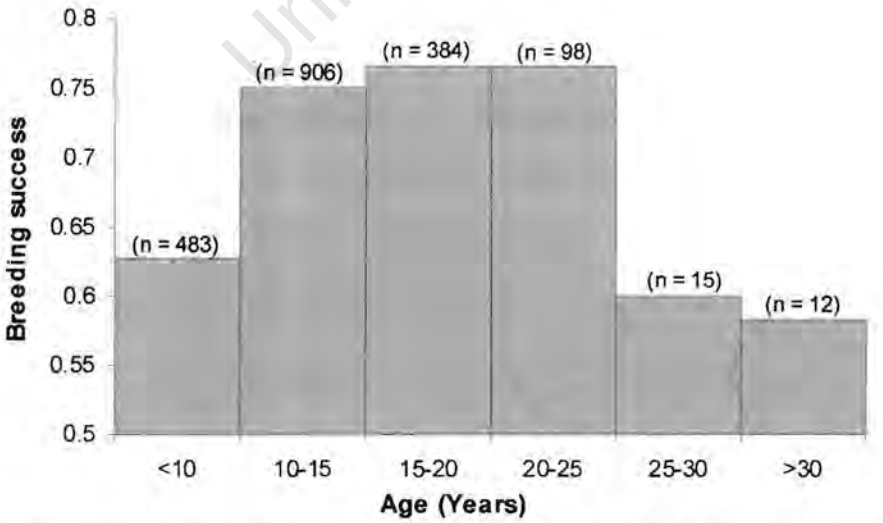

Figure 7.3 Breeding success versus age of wandering albatrosses breeding on Marion Island.

of birds older than 25 years was once again lower (60%). Breeding success of first time breeders (66.4%) was also lower than more experienced birds (74.9%) (χ^2 = 15.1; $P < 0.001$). This was mainly due to hatching success, which was much lower for first time breeders (79.2%) than for more experienced birds (87.3%) ($\chi^2 = 22.4$; $P <$ 0.001).

Most birds (81%) that failed in a breeding attempt in a given year, attempted to breed the following year, whereas most birds (87%) that fledged a chick in a given year attempted to breed only after a full years 'sabbatical' (Table 7.1). These parameters did not vary significantly over the duration of the study.

Table 7.1 The proportion of wandering albatrosses breeding in a given year after a breeding attempt.

Year	% breeding after previous attempt was:	
	Successful	Failed
1	0.7	81.0
2	87.0	13.4
3	7.2	3.2
4	3.0	1.2
>4	2.1	1.0

Mate fidelity and mate loss

Analyses were conducted on all breeding attempts occurring during or before 1995, thus giving sufficient time for a "lost" mate to be resighted. Individuals only recorded breeding once were ignored. Of the remaining 3 984 breeding attempts, 5.3% (n = 210) recorded a mate change. However, only 0.7% (n = 30 breeding events) of breeding attempts were true "divorces" (i.e. the lost mate was resighted alive or breeding after the mate change). In the remainder of the cases the "lost" mate was never resighted again and had presumably died. Following a mate loss, males took significantly longer than females to find a new mate (males = 4.06 ± 1.69 years; females = 2.9 ± 0.7 years; $t = 5.6$, $P < 0.0001$).

Age of first-time breeders

The average age at first breeding for all birds was 9.9 ± 2.9 years. On average, males bred at a slightly older age (10.2 ± 2.8 years) than females (9.6 ± 2.9 years) ($t = 2.59$;

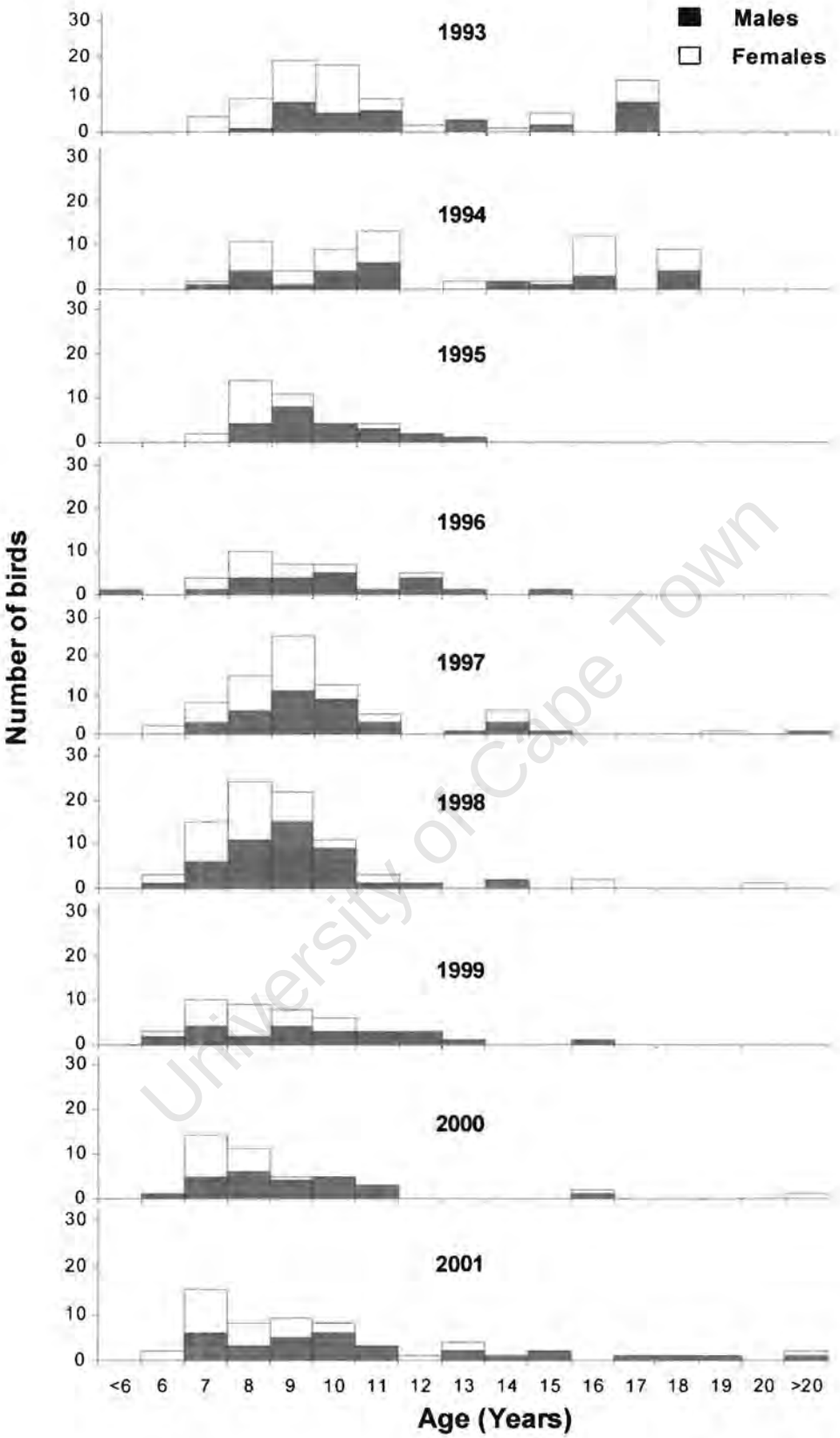

Figure 7.4 The age distribution of first-time breeders in long-term wandering albatross study colonies on Marion Island.

P = 0.01). The average age of first-time breeders for 1997-2001 (10.0) was significantly younger than from 1991-1996 (10.7) (t = 12.2; P = 0.005). The age distribution of first- time breeders also appears to have shifted towards younger age classes during the latter part of the 1990s (Fig. 7.4). Between 1991 and 1996 the proportion of first-time breeders younger than eight years was only 5%, but since 1997 this has increased significantly to 26%. In fact, since 1999, the modal age group of first-time breeders was seven years old (Fig 7.4).The proportion of first-time breeders in the breeding population was significantly correlated with the maximum ENSO index recorded for that year (r = 0.85; P = 0.0074) (Fig. 7.5). This correlation was especially apparent during the large ENSO event of 1997/98.

Juvenile survival and recruitment

The average annual survival of juvenile birds (i.e. <10 year olds) was 89.9 ± 0.004 %. Male juvenile survival (90.1 ± 0.006 %) was very similar to that of females (89.8 ± 0.006 %). Annual survival rate of juveniles varied considerably over the past 13 years (Fig. 7.6), with highest survival rates during the early and late 1990s, and lower during the mid 1980s and mid 1990s.

Recruitment could only be calculated for five cohorts. The average recruitment rate for these cohorts was 33.1% and did not differ between males and females. Recruitment increased consistently between the 1986 and 1989 cohorts, then decreased for the 1990 cohort (Fig. 7.7). However, this latest cohort may be slightly under-represented as these birds were 11 years old at the time of the analysis and a small number of birds may still recruit into the breeding population at an older age.

Adult survival

Overall the annual survival rate of birds older than 10 years was 94.2 ± 0.008 %. Male adult survival was 95.7 ± 0.009 compared to 92.6 ± 0.01 for females. A sex-dependent model was significantly different from a sex independent model (χ^2 = 12.37; P = 0.015). Annual survival of adult breeding birds has varied considerably over the past 16 years (Fig. 7.8). However, it appears that the survival rate of breeders may have increased between 1984 and 1991 (F = 5.859; P = 0.0518). After 1991, adult survival

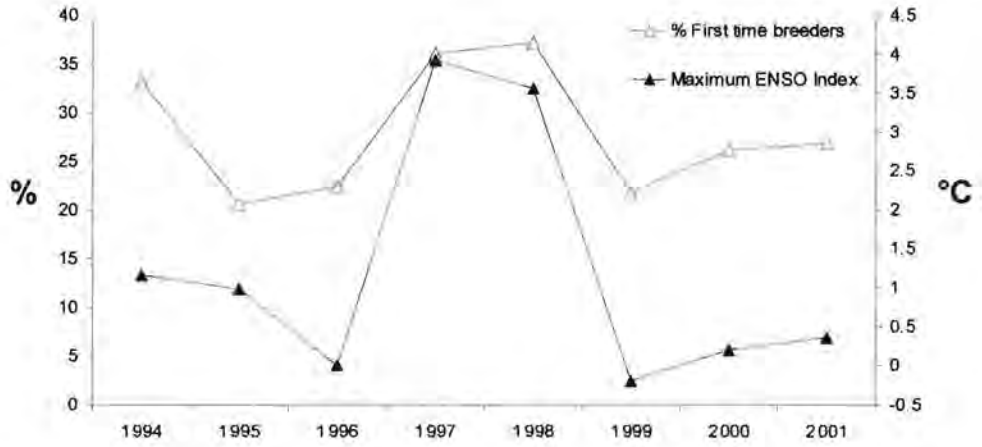

Figure 7.5 The proportion of first time breeders in long term study colonies on Marion Island versus the annual maximum ENSO index (NINO 3).

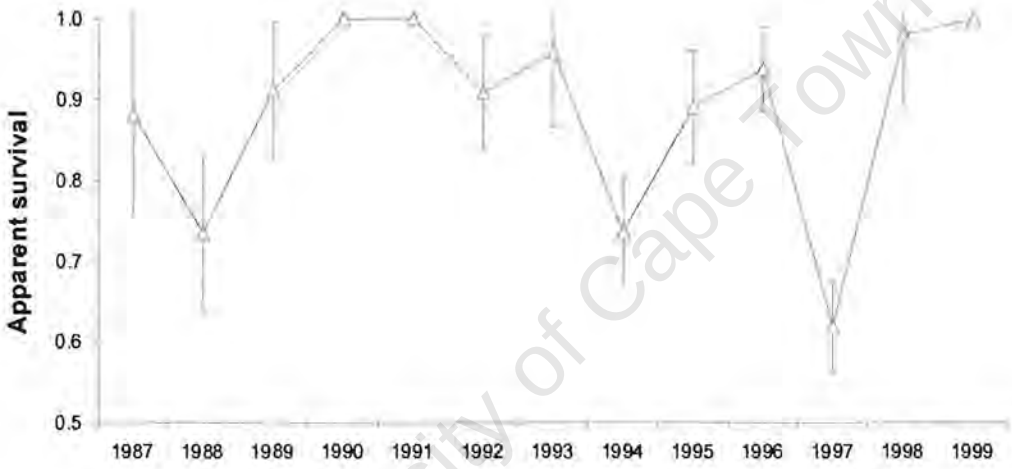

Figure 7.6 Apparent annual survival rates of juvenile wandering albatrosses (1-9 years) on Marion Island

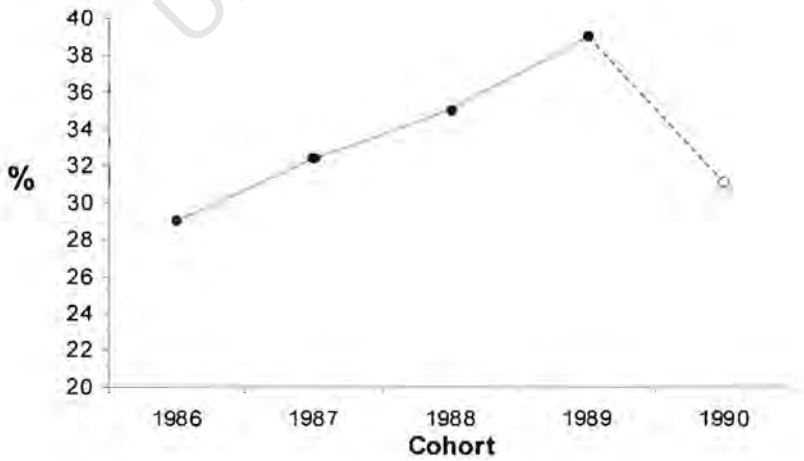

Figure 7.7 Recruitment rates of cohorts of wandering albatross chicks into the breeding population. The measured recruitment rate of the 1990 cohort is probably underestimated (see text).

varied greatly again, but was consistently low between 1994 and 1996. Since 1997, adult survival has been consistently high.

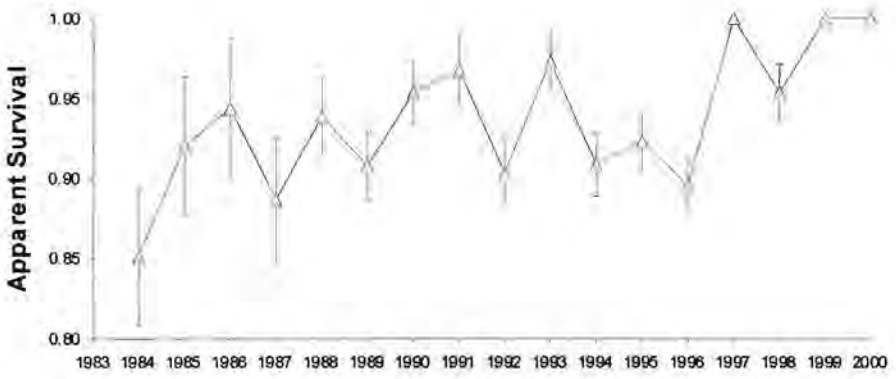

Figure 7.8 Apparent survival rates of breeding adult wandering albatrosses on Marion Island.

Correlations with other populations and longline fishing effort

Pelagic longline fishing effort in the southern Indian Ocean (south of 30°S, 20°E – 141°E) as well as in the vicinity of the Prince Edward Islands (35°S-60°S, 25°E-50°E), has fluctuated considerably over time (Fig. 7.9). Effort the Southern Indian Ocean peaked in the mid-1980s, before decreasing to the lowest levels in more than a decade in the early 1990s. During the mid-1990s effort once again increased, before decreasing rapidly near the end of the 1990s. Effort in the vicinity of the Prince Edward Islands followed a similar pattern to that of the entire Southern Indian Ocean, except that the decrease in effort at the end of the 1990s commenced earlier close to the islands. Japanese longline fishing effort in the Southern Ocean also followed a similar trend except that effort dropped off earlier after the peaks in both the 1980s and 1990s. Annual survival rates of breeding adults and juvenile wandering albatrosses at Marion Island were most strongly correlated (negatively) with the annual effort of the Japanese fleet in the entire Southern Ocean (Table 7.2). Juvenile survival rates were more strongly correlated than adults. However, the survival of breeding adults and juveniles were not correlated with pelagic longline fishing effort closer to the Prince Edward Islands (35°S-60°S; 25°E-50°E) (Table 7.2).

Annual survival rates of adults on Marion Island were significantly correlated with adult survival rates on the Crozet Islands between 1984 and 1991 (the period of overlap between the Marion data and those presented in Weimerskirch & Jouventin

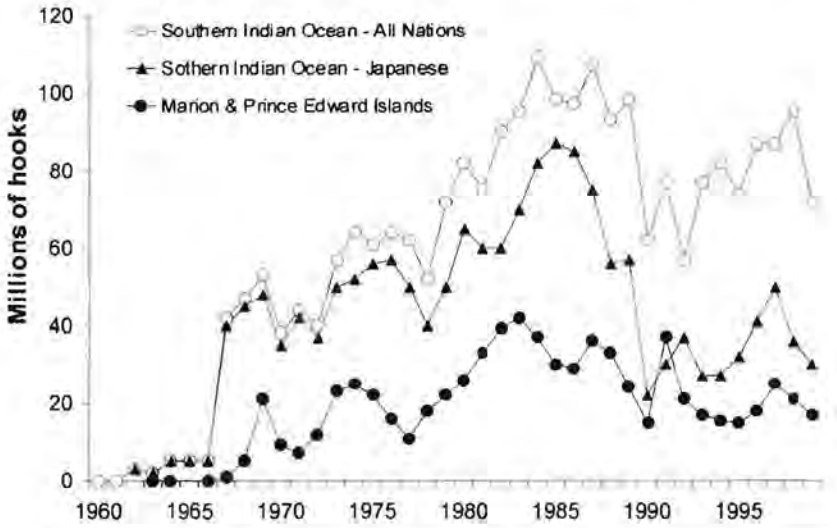

Figure 7.9 Pelagic longline fishing effort in the Southern Indian Ocean (south of 30°S; 20°E-141°E) and in the vicinity of Marion and Prince Edward Islands (35°S-60°S; 25°E-50°E). Adapted from Tuck & Bulman (2001).

Table 7.2 Correlation coefficients of annual survival rates of wandering albatrosses from Marion Island with annual longline fishing effort in the southern Indian Ocean (from Tuck & Bulman 2001).

Age class (years)	Longline fishing effort		
	Prince Edward Islands[1]	Indian Ocean[2] (All nations)	Indian Ocean[2] (Japanese)
Breeding adults (1984-2000)	r = -0.262 P = 0.327	*r = -0.480* P = 0.060	r = -0.534 P = 0.027
Juveniles (1987-2000)	r = -0.228 P = 0.455	r = *-0.400* P = 0.177	r = -0.594 P = 0.025

[1] 35°S-60°S; 25°E-50°E
[2] >30°S; 20°E-141°E

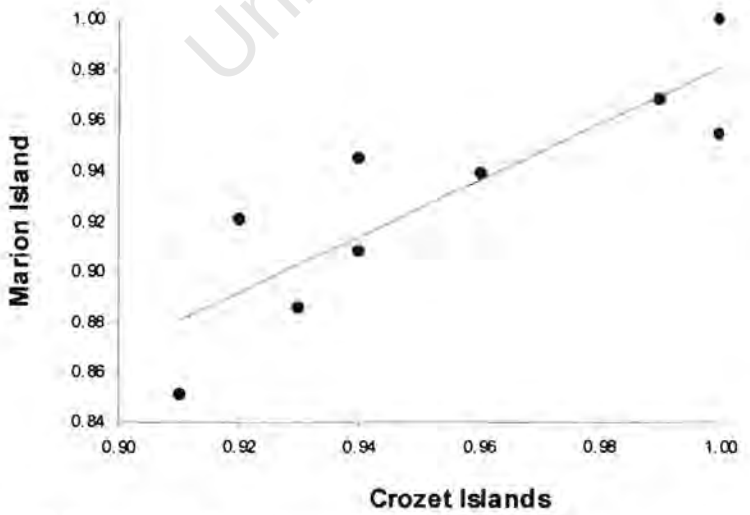

Figure 7.10 Relationship between annual survival rates of adult wandering albatrosses breeding on Marion and the Crozet Islands, 1984 – 1991 (r = 0.818; P = 0.013)

(1998) for the Crozets, Fig. 7.10). Survival rates of adult birds on Marion were not correlated with those recorded for the South Georgia population (Croxall *et al.* 1998) (r = -0.5048, n = 11, P = 0.113).

DISCUSSION

The population of wandering albatrosses breeding on Marion Island has fluctuated considerably over the past three decades. These fluctuations are similar to those recorded on other Indian Ocean Islands (Weimerskirch *et al.* 1997), but differ from the trend on South Georgia, South Atlantic Ocean (Croxall *et al.* 1998). These trends are compared in more detail in Chapter 6.

This Chapter shows that the number of birds breeding on Marion Island is a product of both environmental and anthropogenic effects. Firstly, the proportion of first-time breeders breeding in the study colonies was correlated with the maximum ENSO index. Improved foraging conditions due to changes in environmental variables could allow more young birds to attain a body condition that will allow them to breed for the first time. The physical mechanism behind a possible link between ENSO (as measured in the eastern equatorial Pacific Ocean) and foraging conditions in the Southern Indian Ocean is unknown, but ENSO events are known to affect climate patterns at a global scale. White and Peterson (1996) described an Antarctic circum-polar wave of surface air pressure, sea surface temperature and wind stress, that appeared to be linked to El Niño. Such mechanisms could affect the availability of food resources as well as the ability of birds to find food. For instance, increased wind stress may allow large procellariforms (which are reliant on wind for flight) to forage more efficiently, and thus increase net body condition more quickly. Cooper & Lutjeharms (1992) found a positive correlation between breeding success of yellow-nosed albatrosses *Thalassarche chlororhynchos* and a seasonal 'windiness' index at Gough Island, suggesting that wind stress can be an important factor in foraging ecology of albatrosses. Chapter 6 showed that the residuals of the smoothed population trends of breeding wandering albatrosses and northern giant petrels breeding at Marion Island also were correlated with the maximum ENSO index.

Despite relatively short datasets, the annual survival rates of breeding adult birds and juveniles at Marion Island were negatively correlated with Japanese pelagic longline fishing effort in the Southern Indian Ocean. The lack of a correlation with pelagic longline fishing effort closer to the Prince Edward Islands suggests that a significant proportion of the mortality being suffered by the Marion population occurs when birds move farther away from the islands. This mainly occurs during the non-breeding (sabbatical) year of breeding adults, or during the pre-breeding juvenile years. Tracking studies have shown that non-breeding birds move farther away from the islands and spend more time in the warmer pelagic tuna fishing grounds to the north of the islands (Weimerskirch & Wilson 2000, Chapter 3). At-sea observations suggest that juveniles also make extensive use of these warmer waters (Weimerskirch & Jouventin 1987). Juvenile wandering albatrosses were also killed more frequently in the pelagic longline fisheries along the coast of Australia (Gales *et al.* 1998). In fact, four metal banded wandering albatrosses from Marion Island have been recorded killed in pelagic longline fishing operations around Australia (Gales *et al.* 1998) an area that is only likely to used by non-breeding birds (Chapter 3) or juveniles from Marion Island. However, little is known of the age and sex of birds killed in the vicinity of the subtropical convergence, south of Africa (Ryan & Boix-Hinzen 1998). These foraging areas are closer and more accessible for adult wandering albatrosses breeding on Marion Island (Chapter 3).

The fact that survival rates were more strongly correlated with Japanese pelagic longline fishing in the Southern Ocean compared to that of all nations, can also be explained. Japanese longliners are known to fish farther south (i.e. in the belt 40°S-45°S) than other nations, targeting more profitable southern blue-fin tuna *Thunnus maccoyii* and bigeye tuna *T. obesus* (Tuck & Bulman 2001). Taiwanese pelagic longliners (the other major longline fishing entity in the southern Ocean) mainly target albacore *T. alalunga* and fish mostly north of 40°S (Tuck & Bulman 2001). These correlations were apparent despite no data being available on IUU fishing effort.

The high survival rates observed for breeding adults from 1997 onwards are interesting, as two factors may be at play here. Firstly, Japanese longline fishing effort started to decrease at the end on the 1990s. However, this decrease only started during

1998. More important perhaps, was the development of a demersal longline fishery for Patagonian toothfish close to Marion Island during the latter part of 1996. The legal fishery for toothfish around Marion developed after large scale Illegal, Unregulated and Unreported (IUU) poaching during the austral spring of 1996. Only one wandering albatross is known to have been killed in the legal fishery since its commencement (Chapter 1). However, this fishery produces large amounts of offal in the way of by-catch fish species and Patagonian toothfish heads. During the 1997 season, fishery-derived items (i.e. by-catch species, toothfish heads, or fisheries litter) were recorded in 58% of all diet samples obtained from chicks, and in 76% of samples collected during the early chick-rearing period (Chapter 3). A large supplementary source of food close to their breeding island would not only allow breeding birds to maintain a better body condition throughout the breeding season, but could also cause birds to spend more time close to the islands and less time in the waters of the Sub-tropical Front where the risk of mortality on pelagic longlines is far greater (Ryan & Boix-Hinzen, 1998). These combined effects could result in the higher survival rates of adults observed since 1997. The negative trend in breeding success recorded since 1984 also appears to halt at the end of 1996 and may have even increased slightly since 1997 (Fig. 7.2). This could also be a result of a supplementary source of food closer to the island. However, the advantages of this supplementary source of food for chicks may have been offset in part by the large amount of fisheries litter (i.e. ropes and hooks) that the chicks accumulated (Chapter 2).

The increase in the number of younger birds that attempted to breed since 1997 may also be result of supplementary sources of food (in the form of offal from toothfish longliners) being available close to the island. This would allow younger birds to attain breeding condition, which they would not have been able to do under natural conditions. A decrease in the age of first-time breeders will result in a higher proportion of the whole population that is breeding. Counts of breeding birds (the most frequently used indicator of population trends) would thus give the mistaken impression that the population has increased, when in fact it is just the proportion of birds breeding that has changed (see the population model in the Conclusions and Synthesis). This study showed that both age and breeding experience influenced hatching success. However, a more detailed study by Croxall *et al.* (1992) showed age

to be the more decisive factor in determining egg size and consequently hatching success.

Survival rates of juvenile males and females did not differ, indicating that impacts are probably similar for both sexes in this age group. This could also indicate that juveniles from both sexes forage in similar areas, thus experiencing similar environmental conditions and human impacts. However, adult females suffered higher mortality than adult males. Female wandering albatrosses breeding at Marion Island foraged farther away from the island and spent more time in warmer waters of the subtropical convergence than did males (Chapter 3). Females were thus at higher risk of being killed by pelagic longline fishing vessels concentrated at the Sub-tropical Front, south of Africa. Males also spent more time within the main toothfish longlining areas and would thus derive the greatest benefits from feeding on offal (Chapter 3). The fact that males took longer to re-mate following a mate loss is also indicative of a male-biased population. The time taken for these birds to find new mates results in a significant decrease in the life-time productivity of these birds (Jouventin *et al.* 1999), thus decreasing the fecundity of the population. Unmated males have also been seen to harass mated females holding nests or incubating on Marion Island (pers. obs., PG Ryan pers. comm.). Such disturbance could lead to females deserting nests or eggs being broken.

The correlation between adult survival rates recorded on Marion and Crozet Islands and the lack of correlation with survival rates on South Georgia, suggests that the two Indian Ocean populations are affected by a common underlying cause while foraging at sea. Tuck *et al.* (2001) were able to closely match observed wandering albatross population data from the Crozets using a model that predicted by-catch levels from tuna longline fishing effort. However, for the South Georgia population a fit was only found during the initial population decrease and the subsequent continued population decrease could not be explained by tuna longline fishing effort alone. They concluded that the population trends on the Crozets were influenced primarily by tuna longline effort, whereas the situation at South Georgia was more complex due to its proximity to the Patagonian shelf and the number of longline fisheries present within the foraging range of this population (Neves & Olmos 1998, Schiavini *et al.* 1998, Stagi *et al.* 1998). The similarity of population parameters recorded for Prince Edward

Table 7.3 Comparison of demographic parameters recorded on the three largest populations of wandering albatrosses.

Population	Adult annual survival (post 1980)	Juvenile recruitment (cohorts)	Breeding success
South Georgia[1]	92.0%	27.5%	65.6%
Crozets[2]	95.6%	38.2%	68.5%
Marion Island	94.2%	33.1%	74.6%

[1] Croxall *et al.* 1998
[2] Weimerskirch *et al.* 1997; Weimerskirch & Jouventin 1998

Islands population with those recorded at the Crozets strongly suggests that population trends on the Prince Edward Islands are also influenced primarily by pelagic tuna longline fishing effort. Average adult survival on Marion was similar to that on the Crozets, both of which were substantially higher that that recorded on South Georgia since the 1980s (Table 7.3), suggesting that South Georgia birds experience higher levels of incidental mortality. Juvenile recruitment was higher on the Crozets than Marion and South Georgia (Table 7.3). However, the Marion data only represent five cohorts and therefore are probably not very accurate.

Despite these apparent effects on the population, breeding conditions at the Prince Edward Islands appear to be favourable. Not only do the Prince Edward Islands maintain the largest breeding population of wandering albatrosses (Gales 1998), but mean breeding success was significantly higher than that recorded at South Georgia ($U = 30$; $P = 0.017$) (Table 7.3). The intensity of mesoscale variability at the Sub-tropical Front diminishes from a peak south of Africa to a low point at about 70°E (Lutjeharms & Ansorge 2001), suggesting that the prevalence and intensity of eddies at this front would also decrease. Froneman *et al.* (1999) demonstrated higher primary productivity at the edges of warm-core eddies in this region, and Chapter 5 showed that grey-headed albatrosses concentrated foraging effort around such mesoscale eddies. Marion Island's location relatively close to this highly variable part of the Sub-tropical Front could allow wandering albatrosses breeding on Marion Island to experience favourable foraging conditions.

The conservation of the population of wandering albatrosses breeding on the Prince Edward Islands is therefore of great importance for the species as a whole. Improved conservation status for this species will require a concerted international effort. In this regard, the signing, ratification and implementation of the Agreement on the Conservation of Albatrosses and Petrels (ACAP) (Cooper and Ryan 2001) by all range states (including countries whose vessels and/or nationals are engaged in longline fishing operations in the Southern Ocean) is strongly encouraged. The continued monitoring of this important population breeding on the Prince Edward Islands should also receive high national priority.

Appendix 7.1 Numbers of wandering albatrosses ringed in study colonies on Marion Island. Shaded areas indicate birds that were ringed in the vicinity of the study colonies prior to study colonies being monitored. These birds were treated as known-history birds once they were resighted in the study colonies, but no survival or recruitment estimates were calculated prior to 1984.

Year	Adults	Chicks	Total
1976	32	357	389
1977	1		1
1978	4	289	293
1979	186	109	295
1980		61	61
1981		15	15
1982		84	84
1983	6	250	256
1984	124	101	225
1985	109	72	181
1986	30	312	343
1987	209	286	495
1988	194	157	351
1989	78	135	213
1990	133	190	323
1991	80	191	271
1992	88	237	325
1993	87	195	282
1994	90	160	250
1995	66	192	258
1996	13	181	194
1997	32	193	225
1998	14	215	229
1999	9	197	206
2000	16	185	201
Total	1601	4363	6001

Appendix 7.2 Goodness-of–fit tests of the Cormack-Jolly-Seber model by wandering albatross cohort and all adult birds for the Marion Island population.

Cohort	*p*	*observed deviance*	*expected deviance*	*ĉ*
1976	0.40	277.090	431.252	0.6425
1979	0.18	179.943	146.450	1.2287
1980	0.11	215.344	189.583	1.1359
1982	0.19	373.556	343.044	1.0889
1983	0.16	222.285	191.154	1.1629
1984	0.09	393.207	340.341	1.1553
1985	0.02	114.172	79.617	1.4340
1986	0.14	319.670	285.424	1.1200
1987	0.08	268.692	235.074	1.1430
1988	0.09	267.741	238.446	1.1229
1989	0.10	194.821	167.061	1.1662
1990	0.04	140.224	115.472	1.2144
1991	0.13	83.345	74.398	1.1203
1992	0.03	68.855	48.630	1.4159
1993	0.01	66.838	41.980	1.5921
1994	0.11	10.212	5.336	1.9138
1995	-	0.000	0.000	-
All adults	0.00	9808.459	8608.980	1.1393

p: Probability of a deviance as large or greater than the observed value

ĉ: Estimate of over-dispersion quasi-likelihood parameter, obtained by dividing the observed deviance by the mean of the simulated deviances (a ĉ of 1 denotes a perfect fit)

Appendix 7.3 Elimination of nonsignificant effects from the full CJS model in modelling survival probability in wandering albatrosses from Marion Island: for each model the number of estimable parameters (np), the deviance (DEV), and the Akaike information criterion (AIC) are given

Model		AIC	np	DEV
	Combined cohorts			
(1)	(ϕ(gat), p(at))	10497.359	562	3059.718
(2)	(ϕ(at), p(at))	10143.355	389	3198.444
(3)	(ϕ(t), p(t))	12644.135	42	6402.222
(4)	(ϕ(ga), p(ga))	10292.682	85	3962.326
(5)	(ϕ(a), p(a))	10289.983	43	4046.034
(6)	($\phi_{1\text{-}9}$(g), $\phi_{10\text{-}}$(ga), $p_{1\text{-}9}$(g), $p_{10\text{-}}$(ga))	11994.599	53	5730.222
(7)	($\phi_{1\text{-}9}$(g), $\phi_{10\text{-}}$(g), $p_{1\text{-}9}$(g), $p_{10\text{-}}$(g))	12019.121	8	5845.970
(8)	($\phi_{1\text{-}9}$(c), $\phi_{10\text{-}}$(g), $p_{1\text{-}9}$(c), $p_{10\text{-}}$(g))	12021.001	6	5851.862
(9)	($\phi_{1\text{-}9}$(c), $\phi_{10\text{-}}$(c), $p_{1\text{-}9}$(c), $p_{10\text{-}}$(c))	12023.467	4	5858.338
	Adult breeders only			
(1)	(ϕ(gt), p(gt))	21437.609	84	9808.459
(2)	(ϕ(t), p(t))	21413.578	44	9865.873
(3)	(ϕ(c), p(c))	22177.757	2	10714.600

ϕ: Apparent survival rate
$\phi_{1\text{-}9}$: Apparent survival rate for ages 1 to 9
$\phi_{10\text{-}}$: Apparent survival rate for ages 10 and up
p: Recapture probability
$p_{1\text{-}9}$: Recapture probability for ages 1 to 9
$p_{10\text{-}}$: Recapture probability for ages 10 and up
g: Sex
a: Age
t: Time
c: Constant

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Conclusions and Synthesis

CONCLUSIONS AND SYNTHESIS

The findings of this thesis have led to a clearer understanding of the threat posed by longline fishing mortality to the seabirds breeding on Marion Island. For purposes of simplification, the findings can be loosely grouped into the three sections: 1) understanding the direct and indirect impacts of longlining on seabirds breeding on the Marion Island, 2) the foraging ecology of the two albatross species most affected by longlining, and 3) the population dynamics and demographics of affected species. However, these groupings are artificial and findings within each section are strongly inter-linked. In this synthesis I will highlight these linkages to draw the thesis together.

Direct evidence of impacts

The development of the longline fishery for Patagonian toothfish around the Prince Edward Islands with almost complete observer coverage gave the ideal opportunity to examine the impacts of this fishery in detail. The fact that this fishery developed during the study also allowed the measurement of "before and after" effects. The fishery was located very close to the islands (at least during the first two years), allowing some insights into the foraging ecology of affected birds, which were later corroborated by tracking and diet studies.

It is estimated that between 8500 and 18500 seabirds could have been killed in the Prince Edward Islands toothfish fishery between 1996 and 2000 (Chapter 1). Examination of carcasses killed in this fishery showed that the vast majority of birds killed were adult males that were breeding at the time they were killed, resulting in the maximum possible impact on the demographics (Moloney *et al.* 1994) and life-time reproductive potential (Jouventin *et al.* 1999) of affected populations. It is therefore probable that significant impacts have been made to the populations of white-chinned petrels *Procellaria aequinoctialis*, grey-headed albatrosses *Thalassarche chrysostoma*, Indian yellow-nosed albatrosses *T. carteri* and giant petrels *Macronectes* spp. breeding on the Prince Edward Islands. Chapter 6 shows that some of these populations have shown signs of decreasing during the late 1990s, but

for long-lived seabirds (and in particular biennial breeders) more data are needed to assess these recent population trends (see final section of synthesis).

Chapter 1 also showed that affected species were killed almost exclusively during their breeding seasons, and mostly during the chick-rearing stage. Tracking studies of wandering albatrosses *Diomedea exulans* and grey-headed albatrosses (Chapters 3&4) showed that males foraged closer to the islands than females and that it was particularly during the early chick-rearing stage when the birds showed the highest spatial overlap with toothfish fishing areas. Wandering albatross diet samples also showed that it mainly during the early chick-rearing period that birds showed a high reliance on offal from toothfish longliners. Birds that were not under the constraint of needing to return to feed a small chick frequently (i.e. during incubation, late chick-rearing and in particular, non-breeding) preferred to move farther away from the islands. These findings suggest that competition amongst seabirds for food around toothfish vessels could have been substantial. This competition could be partially the cause of the observed male biased mortality close to the islands. However, this requires that we accept the hypothesis that males are either behaviourally more aggressive than females, or that the larger size of males (Ryan 1999) allows them to gain a significant advantage during competition situations. The observed male bias may also be a product of spatial segregation in foraging areas of the sexes during breeding (see below).

Stomach contents of carcasses, marine debris found around nests, as well as diet studies suggest that there are two assemblages of species that congregate around toothfish vessels: 1) those that specialise in scavenging offal and discards during the hauling and processing of the catch, and 2) those that specialise in attempting to snatch baits as they are being deployed from the stern of the vessel. These assemblages are mainly divided according to physical attributes. Marine debris collected around nests showed that wandering albatrosses aggregated the highest proportion of fishing gear, followed by southern giant petrels and grey-headed albatrosses. Stomach contents of carcasses killed aboard longliners showed that giant petrels contained more offal items, while white-chinned petrels and grey-headed albatrosses contained more bait items. The only wandering albatross killed by the sanctioned fishery contained a toothfish head. Diet studies of wandering albatrosses

showed that during the early chick-rearing stage more than three-quarters of diet samples contained items probably scavenged from toothfish longliners. The large-bodied wandering albatrosses and giant petrels thus appear to have an advantage in scavenging offal. Larger body size has two advantages: larger birds are able to physically dominate in the competition for offal due to their sheer size, and birds with larger gapes are able to swallow larger pieces of offal. The smaller-bodied *Thalassarche* albatrosses and *Procellaria* petrels appear to specialise in attempting to snatch smaller baits from hooks being deployed from the stern. Their smaller, lighter bodies allow them to be more manoeuvrable and able to dive deeper and thus access baited hooks sinking close to the stern of the vessel. This particular segregation probably only occurs at toothfish longliners operating close to the islands during the summer, where the following conditions exist: there is competition for food, large amounts of offal are being produced, and a demersal (i.e. weighted) line is being deployed. The situation at pelagic tuna longline vessels operating farther from the islands (where competition may be less), producing far less offal, and setting unweighted lines will be very different and it is known that a higher proportion of larger *Diomedea* albatrosses are killed in this fishery (Ryan & Boix-Hinzen 1998, Gales *et al.* 1998).

Supplementary feeding on offal around fishing vessels also comes at a price and several carcasses of albatrosses and petrels were found to contain large loads of fishing gear that were more than likely to have been responsible for their deaths. Several birds were also found entangled in discarded fishing gear. Although difficult to quantify, these indirect impacts should be taken into account when assessing the impact of fisheries on seabirds. Importantly, Chapter 2 also demonstrated that it is possible to detect increases in fishing effort in the area where breeding birds forage through the use of standardised searches of nests of albatrosses and petrels, as well as assessing the proportions of fishing gear to 'other' items found next to nests. This non-intrusive method of obtaining information about at-sea threats to these birds is encouraged. It is particularly important as a monitoring tool to detect high levels of IUU fishing effort that occurs around certain breeding colonies of albatrosses and petrels. Many of these colonies are very isolated and monitoring the waters surrounding them by means of conventional methods is logistically very difficult and expensive.

Foraging ecology

The foraging ecology studies of wandering and grey-headed albatrosses (Chapters 3, 4 & 5) produced several findings that are important to our understanding of the interaction of albatrosses breeding on Marion Island with longline fisheries. These findings also corroborate observations of impacts (see above) and help to explain observed changes in population demographic parameters (see below).

The foraging distributions of both wandering and grey-headed albatrosses varied throughout the breeding season, resulting in changes in their spatial overlap with longline fisheries. Birds foraged closest to the islands during the early chick-rearing stage and showed the highest spatial overlap with toothfish longline fishing areas. It was also during this stage that more than three-quarters of wandering albatross diet samples contained offal probably obtained from scavenging around toothfish vessels. This easily-available source of supplementary food may have contributed to high adult survival rates observed since 1997 (Chapter 7). Breeding success also appears to have been affected positively, but the full benefits of this supplementary source of food may have been offset by the negative effect of chicks accumulating large amounts of fishing gear in the form of fishing hooks and rope (Chapter 2).

During the incubation stage grey-headed albatrosses moved farther away from the islands and made extensive use of tuna longlining areas south east of Africa. Wandering albatrosses spent more time in these warmer waters during both the incubation and large chick-rearing stages. However, wandering albatrosses that either deserted their breeding attempt or made abnormally long foraging trips (these were deemed to be more indicative of non-breeding movements) showed the highest overlap with tuna longlining areas both to south east of Africa and to the south west of Australia.

Two important pieces of evidence suggest that it is primarily during the stages when birds move farther away from the islands that most mortality takes place. Firstly, both adult and juvenile survival rates were more strongly correlated with pelagic longline fishing in the entire southern Indian Ocean than with effort in the closer surrounds of the Prince Edward Islands (Chapter 7).

Secondly, overall population trends as well as annual adult survival rates recorded on Marion Island were correlated with those recorded on the Crozets (Chapters 6 & 7), despite the fact that foraging distributions of these two populations were only partially overlapping during incubation and late-chick rearing and almost totally non-overlapping during the early chick-rearing stage. This suggests that these populations are influenced by a common cause that occurs either 1) equally across the at-sea distributions of both populations or, 2) occurs mainly when the two populations show the greatest degree of spatial overlap. If tuna longlining mortality is the main driving force of the Crozet population (as the work of Weimerskirch *et al.* 1997 and Tuck *et al.* 2001 strongly suggests) then the explanation is unlikely to be the former, because tuna longline fishing effort is unevenly distributed across the southern Indian Ocean. It is more likely that the population trends are being driven by incidental mortality that occurs when the two populations show the greatest spatial overlap with each other and tuna longline fishing areas.

Chapter 3 shows that the two populations overlap to some degree during the incubation and late chick-rearing stages. However, these stages correspond roughly to the first and third/fourth quarters of the year. The major proportion of tuna longlining takes place during second quarter of the year (Tuck & Polacheck 1997), which corresponds to the early chick-rearing stage when the foraging distributions of these two populations was almost totally non-overlapping. Preliminary evidence from Chapter 3 and Weimerskirch & Wilson (2000) suggests that the greatest degree of spatial overlap between the distributions of Marion and Crozet birds, as well as pelagic tuna longline fishing, will occur during their non-breeding or sabbatical year. These birds move the farthest from their breeding islands and many spend significant amounts of time south east of Africa or south of Australia in areas of intense tuna longline fishing. Although little is known of the at-sea distribution of juvenile wandering albatrosses, it is likely that they too move farther away from their natal colonies to warmer waters (Weimerskirch & Jouventin 1987) and therefore show a high degree of overlap with pelagic tuna fisheries.

Wandering and grey-headed albatross males made more short foraging trips, and showed a greater spatial overlap with the toothfish longlining areas than females. This

behaviour could be partially responsible for the higher mortality of grey-headed albatross males in toothfish longline operations close to Marion Island. Wandering albatrosses appeared to specialise in scavenging offal rather than snatching baits, thus allowing males to avert this threat and possible gain substantially from this source of supplementary food. Female wandering and grey-headed albatrosses, on the other hand moved farther away from the island and spent more time in the warmer waters where tuna longline fishing takes place. Consequently, female wandering albatrosses are expected be more vulnerable to incidental mortality from pelagic longline vessels. This may be the case, as female wandering albatrosses had a lower survival rate than males (Chapter 7).

Finally, Chapter 5 demonstrated that grey-headed albatrosses were able to locate and exploit highly productive, mesoscale oceanographic features (probably warm core eddies) at both the Antarctic Polar Front and the Sub-tropical Front. These productive oceanographic features are likely to be very important for sustaining the large populations of seabirds that breed on Marion Island. However, they may also pose a threat. Tuna longline fishing vessels are also known to be highly localised around such productive oceanographic features (Uozumi *et al.* 1997). It is therefore possible that the spatial interaction between albatrosses and pelagic tuna longliners may occur at an even finer scale than previously thought. This finding is important when we consider that in the future more vessels are likely to have access to satellite imagery to accurately locate such highly productive oceanographic features, leading to an increased spatial interaction with albatrosses.

Population dynamics

Chapter 6 showed that the population trends of wandering albatrosses breeding on Marion Island were similar to trends of other Indian Ocean wandering albatrosses populations, but differed from that recorded on South Georgia (South Atlantic). Population trends of wandering albatrosses on Marion Island also showed broad scale similarities with three other large procellariforms breeding at the island (grey-headed albatrosses, and northern and southern giant petrels). Although there are probably many different factors that affect the population trends of each of these species and populations, these broad scale similarities suggest a common 'southern Indian Ocean' cause that has an over-riding effect on the demographics of these populations. All four

of these species are killed by pelagic tuna longline fishing, and their broad scale trends can be explained by changes in pelagic tuna longline fishing effort in the southern Indian Ocean over the last three decades. Furthermore there is strong evidence that indicates that the population changes of wandering albatrosses on the Crozets are a result of changes in pelagic tuna longline fishing effort in the southern Indian Ocean (Tuck *et al.* 2001, Weimerskirch *et al.* 1997a). This widespread effect suggests a common cause that occurs when these different species and island populations display the highest degree of spatial overlap with each other and the cause (i.e. pelagic longline fishing). This is unlikely to occur to adults during the breeding season, because the adults of both giant petrels species are mainly scavengers of penguins and seals on the islands during the breeding season (Hunter & Brooke 1992). Mortality to juveniles and adults during the non-breeding season is therefore most likely to be driving these population trends.

Further evidence for this large scale Indian Ocean effect was that annual adult survival rates of wandering albatrosses on Marion were correlated with those measured on the Crozets, but were not correlated with those recorded on South Georgia, Atlantic Ocean (Chapter 7). Furthermore, adult and juvenile survival rates showed signs of being correlated with pelagic tuna longline fishing in the southern Indian Ocean. Interestingly, the strongest correlations were found with Japanese longline fishing in the entire southern Indian Ocean (as opposed to the closer surrounds of the Prince Edward Islands). This suggests that a major proportion of the mortality occurs when birds move farther away from the islands, but are still south of 40°S (where most Japanese effort is concentrated).

Overall, female adult survival rate was lower than males. This is likely to result from the higher spatial overlap of female foraging distribution with tuna longline fishing areas and related risks of incidental mortality (Chapter 3). Finally, interannual variation population numbers appears to be affected by environmental variables. The residuals of smoothed population trends (i.e. interannual variation) of wandering albatrosses and northern giant petrels as well as the proportion of first time breeders in wandering albatross study colonies were significantly correlated with the annual maximum ENSO index. However, the mechanism behind such a link remains unknown.

A population model of wandering albatrosses breeding on Marion Island

A simple age-structured model (similar to that used by Weimerskirch *et al.* 1997a and Waugh *et al.* 1999) was constructed to test if the demographic parameters measured on Marion Island (Chapter 7) could broadly explain the observed changes in the number of breeding birds in the long term study colonies. The model was run for breeding females, because we expect that we are dealing with a male biased population, and thus females are limiting. In terms of survival, age classes 1-9 yrs were classed as juveniles and >10 years as adults. The proportion of birds of each age class that attempted to breed was estimated using average ages at which birds recruited into the breeding population. The proportion of the potential breeding population that actually bred in a given year was calculated from the time that it took birds to breed again after either a failed or a successful breeding attempt (Chapter 7, Table 7.1). Except for the final model, this parameter was kept constant.

When all parameters of the model were set at the means measured for the study period (1984-2000), the population increased at 0.43% per annum, indicating that the population was probably stable or increasing slightly over the study period as a whole. However, as shown in Chapter 7 this was probably a recovery of the population from a low point during the mid 1980s. The population appears to have been much higher during the mid 1970s.

When the year-specific annual adult female survival rates were added to the model, the predicted population showed a steady increase over most of the study period, although for the period 1993-1996, the population decreases slightly (Fig 1a). Adding year-specific juvenile survival caused the predicted population to increase more rapidly from 1989 to 1993, mimicking the observed population (Fig 1b). However, after 1994 the observed population increases steeply to 1998, whereas the predicted population remains relatively constant until 1997, only increasing slowly again at the end of the 1990s. As expected, adding the measured breeding success to this model did not cause the predicted population to change much. Survival and productivity parameters (and therefore changes in the whole population) only appear to be able to explain the observed changes in numbers of breeding pairs up to 1994. However, the observed population is only the proportion of the whole population that attempts to breed in a given year. As demonstrated in Chapter 7, this proportion does not remain

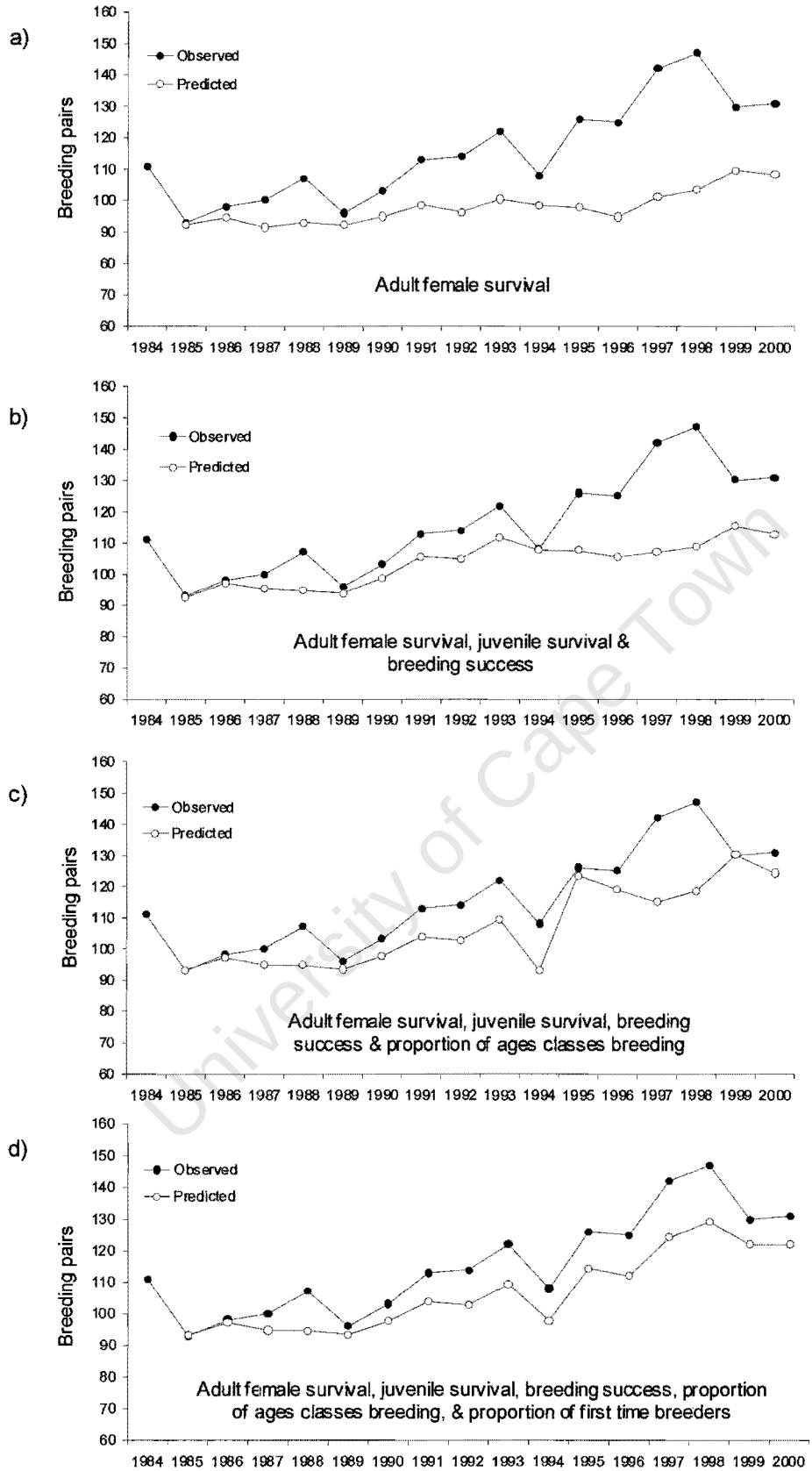

Figure 1. Observed and predicted population changes of wandering albatrosses breeding in study colonies on Marion Island, using an age structured model. Annual parameters that were varied accoring to our measured data, are indicated for each model. Means for the study period were used for all other parameters.

constant and can be affected by several factors, including: 1) the age of first time breeders, 2) the number of juvenile birds that recruit into the population in a given year, and 3) the breeding frequency of adults.

Accordingly, if the proportion of each age class that attempts to breed is allowed to vary according to the measured frequency distribution of the age of first time breeders for each year (Chapter 7, Fig. 7.4), a closer fit is obtained (Fig 1c). Adding this variable causes the trends in the predicted population to match the observed population for most of the study period, and it is only during 1997 and 1998 that the predicted population differs markedly from the observed population. These two years were the strongest ENSO years during this study (Chapter 6 & 7) and they were also the first two years when there were large amounts of supplementary food available from toothfish longliners.

Variation in the age of first time breeders, however does not take into account the actual numbers of first time breeders that will recruit in a given year. As was seen in Chapter 7 (Fig. 7.5), this parameter varied substantially and was correlated with the annual maximum ENSO index, suggesting that environmental variability may cause this variation. This parameter was approximated by changing the proportion of birds that breed each year by the residuals of the mean proportion of the breeding population that is made up by first time breeders. Doing this causes the predicted population to increase for 1997 and 1998 and follow that of the observed population for the entire study period (Fig 1d).

This simple modelling exercise allows some significant insights into the population trends of wandering albatrosses on Marion Island. Firstly, it appears that the population was stable during the 1980s and then increasing between 1989 and 1993. This increase appears to be a real increase in the whole population, resulting from improved adult and juvenile survival during the early 1990s. Arguments presented in this thesis suggest that this increase in survival rates was the result of decreased tuna longline fishing effort (particularly by Japanese vessels) during the early 1990s. However, subsequent to 1994, observed changes in numbers of breeding birds can no longer be explained solely by changes in survival rates (and therefore the changes in

the whole population size). These changes appear to result from changes in the proportion of the population attempting to breed in a given year.

This serves as a warning against the use of short term counts of breeding birds alone to determine the status of populations of albatrosses and petrels. The real impacts of incidental mortality on the seabird populations breeding on Marion Island, resulting from high levels of IUU longline fishing for Patagonian toothfish, may remain masked for several years by changes in the proportion of the whole population that attempts to breed. This may be affected by environmental phenomena (such as ENSO) or anthropogenic effects (such as the availability of supplementary food in the form of offal from fishing vessels). This therefore illustrates the importance of detailed long term monitoring of demographic parameters in order to fully understand the status of threatened populations of albatrosses and petrels.

Future research directions

This study highlighted several differences in the species specific impacts of toothfish longline operations at three sites located close to important seabird breeding islands (Prince Edward Islands, South Georgia and the Crozet Islands). These differences were unexpected given the similarity of the fisheries and the suite of potentially affected species at these three sites. A more detailed comparative study of the fisheries and the affected species at these three sites could yield important clues as to why this occurs.

The tracking work done in this study (as with most tracking studies of seabirds to date), concentrated on the foraging movements of birds during their breeding season. Very little is known about the foraging movements of adult birds during their non-breeding season, or of juvenile birds. This constraint was mainly due to the size of devices (and associated difficulties with longer-term attachments), and battery life. Recently, the development of small leg-mounted Geo-location Sensor (GLS) tracking devices with enough memory and battery power to last through the entire non-breeding season, have made it possible to track adult birds during their non-breeding season (Weimerskirch & Wilson 2000). Findings in this thesis suggest that birds may be experiencing significant longline mortality during their non-breeding season, when they move farther away from the islands. With modern conservation thinking moving

towards marine Important Bird Areas (IBAs) (Skov *et al.* 2000, Nel & Croxall submitted) as a management tool, these studies will become even more important.

There is an urgent need to find out more about the scale and nature of the seabird bycatch on pelagic longliners operating on the high seas of the Southern Ocean. Although logistically difficult, the deployment of skilled scientific observers on these vessels, who can determine the species, sex, age and possibly the provenance of seabirds killed, is of utmost importance. Further refinement of microsatellite DNA techniques in order to be able to accurately determine the provenance of seabirds killed at sea (Double *et al.* 2000) is also a priority.

This study highlighted the demographic similarities between the wandering albatross populations on Marion and the Crozet. A study dedicated to exploring these similarities and possible subtle differences could be very rewarding. Despite a relatively short dataset, this study also showed several interesting correlations with environmental and anthropogenic variables. With continued monitoring and longer datasets these correlations can be explored in more detail using more robust statistical techniques, such as Time Series Analysis and General Linear Models (GLM).

Finally, this study also demonstrated how seabird bycatch rates can be reduced in a demersal longline fishery through the implementation of a few simple mitigation measures. However, reducing bycatch rates in pelagic longline fisheries (where the line is unweighted and baits float for longer) is more difficult. Although seabird bycatch rates in pelagic longline fisheries can be greatly reduced through the use of existing mitigation measures, catch rates typically remain far higher than in well-managed demersal longline fisheries (Gales *et al.* 1998, Ryan & Boix-Hinzen 1998). Research aimed at identifying the most effective and practical ways of reducing seabird bycatch in pelagic longline fisheries is of critical importance to the conservation of albatrosses and petrels.

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Summary

SUMMARY

1. Between 8 500 and 18 500 seabirds are estimated to have been killed by longline fishing for Patagonian toothfish *Dissostichus eleginoides* within the South African EEZ surrounding the Prince Edward Islands, between 1996 and 2000. This was mostly due to the high levels of Illegal Unregulated and Unreported (IUU) fishing, especially during 1996-98. White-chinned petrels *Procellaria aequinoctialis* were killed most frequently, although when lines were set in the day mollymawk albatrosses (*Thalassarche* spp.) and giant petrels (*Macronectes* spp.) were also killed.

2. The vast majority of birds killed by Patagonian toothfish longliners operating around the Prince Edward Islands were breeding adults killed during their breeding season. Highest catch rates occurred when birds were raising chicks. Mortalities of most species showed a strong male bias (>80%).

3. Several important differences were recorded between groups of species killed by Patagonian toothfish longliners that can tell us about their foraging ecology and their interaction with these vessels.
    i. The diurnal foraging albatrosses and giant petrels were killed almost exclusively during the day whereas white-chinned petrels (that forage both diurnally and nocturnally) were caught by both day and night. Night setting still remains the most effective method of reducing catches of albatrosses.
    ii. Albatrosses were killed closer to the islands than white-chinned petrels, indicating their dominance in this area.
    iii. Most albatrosses were hooked in their beaks whereas most white-chinned petrels were hooked in their wings or bodies. This indicates that albatrosses were most likely killed while attempting to snatch a bait, whereas white-chinned petrels were probably killed by hooks that were either flailing around in the air or being dragged through the water.
    iv. The larger-bodied giant petrels' stomachs contained mostly offal, indicating that they preferred to forage at the offal chute during hauling, whereas the mollymawk albatrosses and white-chinned petrels contained mostly baits.

4. A large increase in the amount of fishing gear found next to seabird nests was recorded in association with the start of the Patagonian toothfish fishery around the Prince Edward Islands during the spring of 1996. Wandering albatrosses *Diomedea exulans* accumulated the highest proportion of fishing gear, followed by southern giant petrels *Macronectes giganteus* and grey-headed albatrosses *Thalassarche chrysostoma*. This trend follows body size and corroborates findings from stomach contents of carcasses and diet samples taken on the island. An increase in the occurrence of seabird entanglements and mortalities due to ingestion of fishing gear was also recorded.

5. During their breeding season, both wandering and grey-headed albatrosses varied their foraging distribution and therefore their exposure to the risk of longline mortality. Birds foraged closest to the islands and showed the highest overlap with toothfish longline fishing areas during the early chick-rearing stage. During incubation both species ranged farther from the islands and spent more time in pelagic tuna *Thunnus* spp. longline fishing areas to the north of the islands. Wandering albatrosses also utilised these areas during the late chick rearing stage. Non-breeding wandering albatrosses moved farthest from the islands and spent the most time in tuna longline fishing areas south-east of Africa and south-west of Australia.

6. Female wandering and grey-headed albatrosses foraged farther from the islands and spent more time in pelagic tuna longline fishing areas, whereas males spent more time in the toothfish longline fishing areas. This segregation in foraging areas could be contributing to the observed lower survival rates of female wandering albatrosses (due to higher mortality in the tuna fishery) and the observed male-biased mortality of grey-headed albatrosses in the toothfish longline fishery.

7. A large increase in the occurrence of fisheries derived items in the diets of wandering albatrosses was recorded after the start of the toothfish longline fishery close to Marion Island. The occurrence of fisheries-derived items was highest during the early chick-rearing period, when more than three-quarters of diet samples contained such items. Most of these items could be directly linked to the toothfish longline fishery.

8. Tracking studies also showed how grey-headed albatrosses foraged at highly productive, mesoscale oceanographic features both at the Sub-tropical Front and the Antarctic Polar Front. As pelagic tuna fishing vessels also target these oceanographic features at the Sub-Tropical Front, this behaviour means that the interaction between albatrosses and pelagic tuna longline vessels may occur at a finer scale that previously thought.

9. Long term population trends of four large surface-nesting Procellariformes breeding on Marion Island (wandering and grey-headed albatrosses, and northern and southern giant petrels) displayed similar broad scale population changes. All were stable or decreasing slightly during the 1980s, increased during the early 1990s and then either decreased or stabilized again during the late 1990s. These trends could be broadly explained by changes in longline fishing effort in the southern Indian Ocean.

10. Population counts of wandering albatrosses breeding on Marion Island were correlated with counts of other Indian Ocean populations, but were different from counts from the South Atlantic population on South Georgia, suggesting a common underlying cause that is driving trends in the Indian Ocean populations.

11. The residuals of smoothed population trends of wandering albatrosses and northern giant petrels were significantly correlated with the maximum ENSO index. This means that although long term trends are likely to be driven by a cause that has a more sustained effect, interannual variation in the numbers of birds attempting to breed appears to be affected by environmental variation (as recorded by the ENSO index). Although the effects of ENSO are known to be widespread, the mechanism behind a link between the ENSO index, as measured in the eastern equatorial pacific, and these Indian Ocean populations remain unknown.

12. Annual adult survival rates of wandering albatrosses breeding in study colonies on Marion Island were correlated with those recorded on the neighbouring Crozet Islands, but were different from those recorded in the South Atlantic population on South Georgia. This also suggests that a factor common to the southern Indian Ocean is driving the populations in this region. Evidence from work on the Crozet

Islands and this study suggests that the cause for the observed population changes is incidental mortality in the pelagic tuna longline fishery.

13. Adult and juvenile survival rates of wandering albatrosses were more strongly correlated with Japanese longline fishing effort in the entire southern Indian Ocean than with fishing effort reported closer to the island. This suggests that a significant proportion of mortality occurs farther away from the islands, but south of 40°S (the area mostly used by Japanese vessels). As in other populations, female adult survival was significantly lower than males, suggesting that females may be suffering higher mortality in pelagic tuna longline operations due to higher spatial overlap with this fishery while foraging.

14. Since 1997 a marked increase in wandering albatross adult survival, a decrease in the age of first-time breeders, and a slight increase in breeding success was observed. This could be partially the result of increased availability of large amounts of supplementary food close to Marion Island, in the form of offal from toothfish longliners. However, the benefits to breeding success were probably offset in part by the large amount of fisheries-derived debris that was fed to chicks.

15. The proportion of first time breeders in the study colonies was correlated with the maximum ENSO index, indicating that environmental variation is an important factor in determining whether first-time breeders are able to attain breeding condition.

16. An age-structured model of the wandering albatross population showed that the observed increase in numbers of breeding birds between 1989 and 1994 could be explained by changes in adult and juvenile survival rates. However, the subsequent increase between 1994 and 1998 appears to be the result of a change in the proportion of the whole population that was breeding. This was the result of a decrease in the age of first-time breeders as well as variation in the proportion of first-time breeders that is recruited into the breeding population in a given year. This warns against reliance on short-term counts of breeding birds to determine the status of albatross and petrel populations. It is also possible that the long term impacts of the high levels of IUU toothfish longlining on the seabirds breeding on Marion Island, may be masked by these effects.